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Assessment of cross-border anthropogenic pressure on groundwater state in PL-UA and LV-EE pilot areas

June 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.

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Scientific Editor	Tetyana Solovey (*Polish Geological Institute - National Research Institute*)
Authors (*Polish Geological Institute – NRI*):	Tetyana Solovey, Rafał Janica, Małgorzata Przychodzka, Hanna Kolos, Anna Gryczko – Gostyńska, Tetiana Melnychenko
Authors *(Zahidukrgeologiya)*:	Natalia Pavliuk, Liubov Yanush, Halyna Medvid
Authors (*Ukrainian Geological Company*):	Volodymyr Klos, Yurii Kharchyshyn
Authors (*Latvian Environment, Geology and Meteorology Centre*)	Dāvis Borozdins, Jekaterina Demidko, Krišjānis Valters
Authors (*Geological Survey of Estonia*)	Magdaleena Mannik, Marlen Hunt, Andres Marandi, Liina Hints
Authors (*University of Latvia*)	Jānis Bikše, Inga Retike
Authors (*Norwegian Geological Survey*)	Belinda Flem
Authors (Norwegian Water Resources and Energy Directorate)	Lars Stalsberg
Project coordinator	PGI-NRI

Document summary

The goal of this report was to analyse significant anthropogenic pressure factors along with the assessment of their influence on water state. These factors include: water abstraction from intakes and drainage systems of open-pit mines, mine wastewater and sewage discharges. In the areas, where groundwater is affected by transboundary impacts, all the factors and anthropogenic impact have been identified. Data on specific pollutant load as a result of anthropopressure and amount of groundwater abstraction had been collected. Data on natural groundwater vulnerability to pollution were aggregated and the assessment of the impact of anthropopressure on the groundwater state was carried out.

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Preface

This report has been prepared as part of the EU-WATERRES (EU-integrated management system of cross-border groundwater resources and anthropogenic hazards; www.euwaterres.eu) project, funded by the EEA and Norway Grants Fund for Regional Cooperation. The project aims to analyse significant anthropogenic pressure factors along with the assessment of their influence on groundwater state. These factors include: water abstraction from intakes and drainage systems of open-pit mines, mine wastewater and sewage discharges. In the areas, where groundwater is affected by transboundary impacts, all the factors and anthropogenic impact have been identified. Data on specific pollutant load as a result of anthropopressure and amount of groundwater abstraction had been collected, analysed and presented. Data on natural groundwater vulnerability to pollution have been aggregated and the assessment of the impact of anthropopressure on the groundwater state have been carried out.

With this report one but final step to establish lasting and close cooperation with partners and key international decision makers has been made and the basis for development of a "Program of protection of transboundary groundwater against pollution and depletion on the eastern border of UE" had been established.

b.g.l.	below ground level
BAB	Baltic Artesian Basin
BOD5	Biological Oxygen Demand
CA	Competent Authority
CDR	Central Data Repository
CEF	Central Enrichment Factory
CLC	Corine Land Cover
COD	Chemical Oxygen Demand
DF	Driving Forces
EC	European Commission
ECE	Economic Commission for Europe
EEA	European Economic Area
EEA	European Environment Agency
EFTA	European Free Trade Association
EQS	Environmental Quality Standards
ESA	EFTA Surveillance Authority
EU	European Union
GIS	Geographic Information System
GW	Groundwater
GW WG	Working Group on Groundwater
GWB	Groundwater Body
HPP	Hydroelectric Power Plant
ICPDR	International Commission for the Protection of the Danube River
IRBD	International River Basin District
ISRBS	International Sava River Basin Commission
MS	Member State
MUA	Main useful aquifer
OECD	Organization for Economic Cooperation and Development
OTG	об'єднана територіальна громада, Territorial Community (in Ukraine)
PoM	Programme of Measures
QA	Quality Assurance
RBD	River Basin Districts

RBMP	River Basin Management Plan
SME	Small Medium Enterprise
TBA	Transboundary aquifer
WFD	Water Framework Directive
WFD	Water Framework Directive (2000/60/EC)
WG DIS	Working Group Data & Information Sharing

Assessment of cross-border anthropogenic pressure on groundwater state

Part 1. Water Framework Directive – Implementation and perspectives

Part 2. Assessment of cross-border anthropogenic pressure on groundwater state in the Polish-Ukrainian pilot area

Part 3. Assessment of cross-border anthropogenic pressure on groundwater state in the Latvian-Estonian pilot area.

Part 1. Water Framework Directive – Implementation and perspectives

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1. Water Framework Directive – Implementation and perspectives

1.1 Implementation and perspectives in an EU-member country

Implementation

Estonia and Latvia share approximately 300 kilometers long border. Both countries are located in the northern part of the Baltic Artesian Basin (BAB), which is a complex and multilayered hydrogeological system situated in the western part of the East European – Platform. The BAB, encompassing an expansive area of around 480,000 square kilometers, extends across the territories of Estonia, Latvia, Lithuania, as well as parts of Russia, Poland, and Belarus (Virbulis et al 2013). The transboundary aquifer system between Estonia and Latvia encompasses an expansive area of approximately 8000 square kilometers. This aquifer system primarily includes the Gauja-Koiva and Salaca-Salatsi transboundary river basins, which are situated within the territories of Gauja RBD and Daugava RBD in Latvia, as well as three RBDs in Estonia, namely Koiva, West Estonia, and East Estonia (Vallner & Porman 2016). Transboundary aquifers between Estonia and Latvia all take art in today's water cycle. The recharge takes place in uplands and the flow direction is governed by local depressions, valleys and surface water bodies. The transboundary flow mostly takes place in the eastern and central part of the shared aquifer system area where mostly the groundwater direction is from Estonia to Latvia (Solovey et al 2021).

The inclusion of transboundary water management in national legislation took place in 1992, when both Estonia and Latvia signed the Water Convention, which is an agreement under the United Nations Economic Commission for Europe (UNECE). Subsequently, after the accession of both countries to the European Union in 2004, the principles of the Water Framework Directive (WFD) were integrated into their respective national legislation. Although a bilateral agreement regarding transboundary water management had been established between the Ministries of Environment of Estonia and Latvia in 2003, there was limited tangible activity in this area until 2018. However, in 2018, a joint project named GroundEco was launched with funding provided by Interreg Estonia-Latvia programme. The primary objective of this project was to facilitate sustainable management practices and the establishment of shared principles for transboundary groundwater resources management with emphasis on groundwater dependent terrestrial ecosystems. Prior to 2018, the management and monitoring of the EE-LV aquifer system area were conducted independently, as indicated in Table 1.

Table 1. The development of systematic groundwater monitoring networks in Estonia and Latvia

Years	Latvia	Estonia
1959-1976	**Local scale** (designed in a way to address specific needs: (1) development of new well fields for water supply, planning of land amelioration, monitoring of level rise near hydroelectric power plants (HPPs), assessment of sulphide rich groundwater potential for balneology (1959 ~50 wells in unconfined aquifers → 1975 ~620 wells covering whole country)	Groundwater monitoring started in **1960** to monitor the status of groundwater in different conditions (in natural conditions, in areas of intensive groundwater use in the largest cities, in mining areas, in groundwater pollution sites). In total, there were seven observation areas, each with its
1976-1992	**Local scale** (all previously mentioned + open pit	

	mines, contaminated areas) **and regional** (were developed based on the known hydrodynamic properties of large-scale groundwater systems and major pressures in order to monitor natural and disturbed conditions (monitoring stations principle). Emphasis on Riga, Jurmala and Liepaja vicinities – known aquifer overexploitation).	own monitoring program based on local issues. One of the observation areas was about the natural conditions on a **regional scale**. In 1961, there were 215 monitoring wells, in 1990, there were already 760 wells.
1993-2002	Due to the collapse of SU the monitoring carried out without particular aim (business as usual, voluntarily). There are years when monitoring is carried out only in some parts of Latvia.	From **1990**, due to the collapse of the SU, there was a break in groundwater monitoring. Monitoring was conducted by water companies, mining companies and companies associated with pollution sites. In **1995**, the national monitoring program was created; the status of groundwater was (similar as before) assessed in seven observation areas with different conditions: intensive water use, mining areas, agricultural impact on karst areas, in areas disrupted by intensive groundwater use and in regional scale in natural conditions.
2006-2008	Aimed to provide data for GWB characterization, improvement of monitoring networks (many «white» sports – DW monitoring only in SW, no operational monitoring)	Since **2005**, the quantitative and chemical status of groundwater were assessed by groundwater bodies (or groups of groundwater bodies) within the framework of the National Environmental Monitoring program's sub-program for groundwater monitoring
2009-2014	aimed to provide data for quantitative and qualitative assessment of GWB status (+ risk assessment), identify negative trends of pollutants, monitoring in protected areas and support decision making. Cut due to the economic crisis and we still deal with the lack of data from that time.	
2015-2020	The strategic objective was to provide necessary data for status assessment of GWBs. Specific objectives remained the same.	Since **2014**, the strategic objective has been to provide necessary data about the chemical and quantitative status for status assessment of the GWB-s.

The initiation of the Water Framework Directive (WFD) implementation in Estonia commenced in 2000 with the delineation process of groundwater bodies. By 2004, the initial version of groundwater bodies had been officially confirmed. Subsequently, in 2013, the WFD methodology for assessing Estonian groundwater bodies and determining threshold values was developed. This methodology was supplemented by the Groundwater Standards and Guidelines in 2019. Based on this established framework, the status of the existing 31 groundwater bodies in Estonia is assessed every six years, specifically in 2014 and 2020. These assessments play a crucial role in shaping decisions related to the national groundwater monitoring plan, demonstrating the direct influence of the WFD implementation on such strategic determinations.

In Latvia, the adaptation of EU WFD requirements started similarly to Estonia in the early 2000s. The requirements of the WFD are transposed into the national legislation. Also, the WFD implementation is based on an integrated river basin catchment approach. Since 2004, the water status assessment system has been periodically improved. The first delineation of groundwater bodies (16 at that time) was finalized in 2004, while the first national groundwater monitoring program was prepared in 2007. The methodology for assessing the status of groundwater bodies in the 1st and 2nd cycle RBMPs was largely based on expert judgment, while in 3rd cycle RBMPs the assessment was improved by developing/ improving assessment methodologies, including more detailed information and wider range of data (including groundwater ecosystems, threshold values and results of EU funded projects). GWBs were also revised (according to WFD requirements - every six years), because of which the total number of GWBs increased from 16 to 25.

Implementation challenges and perspectives

Managing river basins and international river basins that span across country borders poses various challenges due to differences in delineation methodologies and limited transboundary cooperation. The Water Framework Directive (WFD) acknowledges two types of river basins: River Basin Districts (RBDs), which extend beyond national borders, and International River Basin Districts (IRBDs), located in areas adjacent to the border. In Latvia, the Gauja and Daugava serve as RBDs, while Estonia comprises three RBDs: Koiva, East-Estonia, and West-Estonia. Unfortunately, the low level of transboundary cooperation between the countries has led to discrepancies in the delineation RBDs and groundwater bodies. Now, these discrepancies complicate joint assessment of shared groundwater, and reporting to European Commission. While harmonization of approaches would be time consuming and expensive and would strongly affect future evolution process of WFD implementation due to changes management units.

Transboundary aquifers between Estonia and Latvia are characterized by a sparse population and the absence of significant industrial activities leading to a lack of emphasis on collaborative groundwater management efforts. Nevertheless, it is worth noting that both Estonia and Latvia have established working arrangements with other neighbouring countries. Estonia has a cooperative arrangement with Russia, while Latvia maintains a partnership with Lithuania.

Despite the presence of a cooperation agreement between water specialists from Estonia and Latvia, their collaboration is irregular and largely contingent upon the successful acquisition of project funding from local or regional sources. To ensure that decisions regarding groundwater systems are informed by an accurate understanding, hydrogeologists should engage in effective communication with various disciplines, policymakers, and society as a whole. Currently there is low awareness of groundwater protection in general.

Cooperation on transboundary aquifers is crucial for several important reasons.

Firstly, collaboration is essential to effectively manage and sustainably utilize these shared groundwater sources. Without cooperation, there is a risk of conflicts and disputes arising over water rights and access (especially in changing climate context), which can negatively impact both the environment and human populations. Moreover, transboundary aquifers are increasingly facing challenges due to factors such as climate change, population growth, and competing water demands. Cooperation allows for joint efforts in addressing these challenges, pooling resources, and implementing sustainable solutions. It promotes the sharing of best practices, technological advancements, and capacity-building initiatives, benefiting all countries involved.

Secondly, groundwater knows no political boundaries and operates as a connected system. The actions taken by one country regarding groundwater extraction or pollution can directly affect the quantity and quality of water in neighbouring countries. Therefore, cooperation is necessary to establish shared policies, regulations, and monitoring mechanisms to ensure the responsible and equitable use of transboundary aquifers.

Thirdly, transboundary aquifers are often characterized by complex hydrogeological dynamics that require specialized expertise for their management. By collaborating and sharing knowledge, countries can benefit from the collective understanding and experiences of all involved parties. This can lead to improved scientific research, data sharing, and the development of effective management strategies.

Lastly, cooperation on transboundary aquifers fosters diplomatic relations between nations, promoting goodwill, trust, and mutual understanding. It provides a platform for dialogue, negotiation, and the establishment of agreements that can ensure long-term water security and shared benefits.

In summary, cooperation on transboundary aquifers is crucial to foster sustainable management, prevent conflicts, optimize resource utilization, and promote environmental and socioeconomic well-being for all countries involved. It is a strategic approach that recognizes the interconnected nature of groundwater systems and the need for collective action to safeguard this vital resource.

1.2 Implementation and perspectives in an EEA-EFTA country (NVE/NGU)

The WFD has been adopted by countries associated to the European Economic Area (EEA) and the European Free Trade Association (EFTA), Iceland, Liechtenstein and Norway, at the same level as EU-Member states. In this section, the implementation of the WFD and its perspectives from an EEA-EFTA point of view, with emphasis on Norway, are reviewed.

The WFD was incorporated into the Agreement on the EEA-EFTA area by Joint Commission Decision No 125/2007 of 28 September 2007. However, the formal incorporation was delayed until 2009 due to Iceland's negotiations with the European Commission on special adaptations to the directive (Entson and Gipperth, 2010). The EU Member states implemented the WFD from year 2000 and have at present entered their 4th reporting period while the EEA-EFTA countries are delayed by one 6-year cycle. EEA-EFTA countries have thus entered their 3ed reporting period. The historical implementation of the WFD by the EEA-EFTA countries Iceland and Norway is well described by Halleraker et al. (2013). Flem et al. (2022) have recently presented a summary of present status of the implementation in Norway.

Background information on the implementation of the WFD

Norway carried out an informal pilot for the 1st cycle of the WFD reporting. The pilot consisted of selected river basins, representing typical river basin types across Norway. River Basin Management Plans (RBMPs) for these were produced and uploaded to the Central Data Repository (CDR) in addition to electronic data for WFD articles 3 and 5. Based on the pilot Norway received an evaluation from the EFTA Surveillance Authority (ESA) with recommendations for improvement (EU, 2012).

The second reporting cycle, with deadline 22 March 2016, was the first obligatory reporting of River Basin District Management Plans (RBMP) for the EEA/EFTA countries. In this cycle, Norway had 18 River Basin Districts (RBD) where of 12 were International River Basin Districts (IRBD). Two of the IRBD drain towards Finland and four towards Sweden. The remaining sex IRBD were Norwegian RBDs with parts in Finland and Sweden. The transnational cooperation within the IRBDs varied widely from IRBD to IRBD. Only one separate plan for one of the IRBDs originating in Norway and draining towards Sweden were made (https://www.vannportalen.no/plansyklus/planperioden-2016---2021/regionale-vannforvaltningsplaner-2016---2021/), as asked for in the WFD, and one Roof report for the Norwegian-Finish IRBD. The other IRBDs were mentioned in separate chapters in the RBMPs covering the adjoining Norwegian RBDs. For all IRBDs there were a varying degree of transnational cooperation. In contrast to the RBMPs, the electronic classification data etc. were uploaded to the CDR for all IRBDs.

Only geometry in addition to basic information was uploaded to the CDR for groundwater. Groundwater was not mentioned in the RBMPs nor the Programmes of Measures (PoM), as it was politically decided to put it aside and focus on surface water (Flem et al., 2022). The reason for this might be the perception of groundwater as less important in Norway. Most of the information asked in the reporting was omitted as no data were available.

As for many EU member states the reporting of the second cycle (Norway's first cycle) got delayed due to a lengthy preparation of the data for the CDR. Norway have many waterbodies due to its geography. Using data in the scale of 1:50 000, a total number of 28242 surface waterbodies and 1394 groundwater bodies are delineated. The large amount of geographical data caused challenges for the CDR and the QA processes. Hence, the entering of the data into the CDR and the running of the QAs was time consuming. For the relational data there were fewer problems as soon as the data were internally consistent. The Access database prepared as a reporting tool by the Commission were used, which simplified the reporting process to a large degree. The data to the CDR was approved 1st August 2018. Norway has not received any evaluation of the reporting from ESA and no clear explanation why.

The third reporting cycle with deadline 22 March 2022 is the second mandatory cycle for the EEA/EFTA countries. During the second sex year reporting cycle a regional reform was taken place in Norway valid from 1 January 2020. The new delineation of counties resulted in altered RBD areas, where some were split and some merged. Therefore, Norway had in total 16 RBDs, where of 11 IRBDs, at the time of the third reporting cycle. As for the previous cycle the transnational cooperation has varied. For this cycle two separate plans are made for two IRBDs draining to Sweden, Bothnian Sea and the Skagerrak and Kattegat. For the Norwegian-Finnish IRBD a separate plan for the Finnish part has been made in Norwegian in cooperation with the Finnish Competent Authority (CA). For the Bothnian Bay IRBD a common strategy document has been produced between the Swedish and Norwegian CAs. As for the remaining IRBDs these are only mentioned in separate chapters in the RBMP for the adjoining Norwegian RBD.

In the third cycle, the focus in Norwegian has again been on surface water. Groundwater has not been prioritised (Flem et al., 2022), so there are no more data to report to the CDR as for the 2016 reporting. The exception is some monitoring data for a few reference waterbodies (e.g., Dagestad et al., 2020 a; Dagestad 2020b). Groundwater is not included in the RBMPs nor the PoMs.

For the third reporting cycle there are huge delays for most EU member states in uploading approved RBMPs, PoMs and electronic data to the CDR. The delay of the RBMPs and the PoMs are mainly caused by political approval processes. For the reporting of electronic data to the CDR there are technical challenges, both for the geometry and the relational data. For this cycle Norway has 32 400 surface waterbodies and 1 401 groundwater bodies. This has again challenged the CDR capacity and caused a delay in the reporting process. The Access database prepared by the Commission is used for the relational data as for the previous cycle. Correspondingly with the previous reporting this simplifies the reporting process as there are internal checks in this database which prevents errors.

Challenges in the EEA/EFTA countries

The WFD is the most extensive framework directive on environment in the EU and EEA/EFTA area, which poses challenges for both the EU and the EEA/EFTA countries, both in organising, planning, and reporting. Most of the challenges are the same for all countries, but there are two main differences concerning the EEA/EFTA countries. One difference is that because EEA/EFTA countries are a six-year cycle behind the EU member states, adjustments must be made in the CDR when they are reporting. Secondly, there are no consequences for missing/delayed reporting of RBMP and PoM which may e.g., cause reduced funding for implementation of the WFD.

Organisation of the WFD work

One common challenge in organising the administration of the water management in line with the WFD is to break up old habits. It has been and still is in most countries split between different sectors with diverting interests, where they oversee different aspects of the water resources. The aim of the WFD has been and is to reduce this fragmentation of the water management to achieve a holistic approach to water management. There has been improvement in many countries, but the EU Commission has commented on the lack of progress in several WG DIS meetings.

To organise the water management in line with the WFD Norway has set up an organisation across water related sectors from the ministries on the top down to the municipal level (Solli., 2020). 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 lover level of subdivisions of the RBDs. In this way the organisation of the WFD work is well implemented on all levels. According to the OECD Norway has got a successful implementation of the cross-sectoral and public cooperation (OECD, 2022). However, OECD does not have the detailed knowledge about the planning and reporting process, which is natural. The CDR is a source for more detailed information on the implementation of the WFD. If a country has problems with reporting according to the CIS, it is a sign of lack of implementation. The contemporary report for 22 March 2022 shows that both financing and measures are lacking in many areas, however, the report will not be publicly available until 2024.

The creation of the RBMPs and PoMs

The preparation of the RBMPs and the PoMs is another challenge. Classification of waterbody status, monitoring, creation of plans and measures are huge and resource demanding tasks. When the plans and measures are ready, these must go through a political approval process, which is not always straightforward. The approval process and adjustments of the RBMPs and PoMs takes time in most countries.

To prepare RBMPs and PoMs in line with the WFD guidance has been challenging in Norway as the national responsibility as CA is the County Municipalities, which is a political entity within each county. Previously, this responsibility was placed with the County Governors, which represent the state and secured a direct line from the Ministry of Climate and Environment to the CAs. When the County Municipalities took over the responsibility as CA this line of command was lost (Norsk Vannforening, 2008). This complicated the WFD work, as the CA could not be instructed by the ministry to follow the guidelines in the Common Implementation Strategy (CIS) guidance's in the production of the RBMPs and the PoMs. As a result, the Norwegian RBMPs and the PoMs did not contain all information requested in the guidance's. One challenge was the fulfilment of the WFD article 11 and 13 in creating separate IRBMPs and PoMs for the IRBDs. Although, both the RBMPs and the IRBMPs with their PoMs have been improved for the last reporting cycle, these are still not fully in line with the WFD.

A major difference between the EEA/EFTA countries and the EU member states, which may have an important influence on the work is that there cannot be put any sanctions on the non-member states if the WFD is not fulfilled. The member states can be taken to court and will be penalised, while the EEA/EFTA countries will not get such reaction to a breach of the directive. It is not that one does not try to fulfil the WFD, but a risk of consequences would help on the allocation of resources to the WFD-work.

In the presentation of water management challenges in the Norwegian newspapers, or other media, the WFD as a forceful tool is rarely mentioned. One example is the challenge with runoff of nutrients from agricultural farming to the Oslo fjord, where not even the government site mentions the obligations to the WFD, and that the WFD can be used as a tool to change the situation (KLD, 2023).

The minimal focus on groundwater might be a result of the lack of consequences for Norway, if not reporting according to the WFD. As described above little data on groundwater was reported for the 2016 reporting, and not much more for the 2022 reporting.

In the case of Iceland, only the RBMP and PoM will be reported for the third cycle, in addition to the geometry and one XML file to the CDR for the RBD SUCA, which contains data for the RBD, SubUnits and the CA. The reason for this is that this is the only legally binding delivery to the WFD. The delivery of the descriptive data in XML is only within the CIS, and not legally binding – yet. This might change if the member states do not deliver as agreed by the national Water Directors.

The reporting to the CDR

The biggest challenge in the reporting to CDR is the one-cycle delay in the reporting of the WFD for the EEA/EFTA countries. The WFD was incorporated into the Agreement on the European Economic Area (EEA) by Joint Commission Decision No 125/2007 of 28 September 2007. However, the formal incorporation was delayed until 2009 due to Iceland's negotiations with the European Commission on special adaptations to the directive (Entson and Gipperth, 2010; Halleraker et al., 2013). In 2010 the ESA Surveillance Authority sent a final warning to Iceland and to Liechtenstein for their failure to implement the Water Framework Directive into national law, https://www.eftasurv.int/newsroom/updates/environment-iceland-and-liechtenstein-fail-implement-water-framework-directive. Iceland's position was that there were no water bodies negatively affected by anthropogenic activities 200 meters above sea level. The Islandic demands on special adoptions were not accepted by the EU Commission, as they cannot make exemptions for one country only. Since these negotiations took time, the reporting for the EEA/EFTA countries had to be delayed by one cycle. Given that there is only one CDR available for both member states and the EEA/EFTA countries, this has complicated the reporting, both for the EEA/EFTA countries and the EU Commission.

The reporting of the RBMPs, PoMs and other documentation is a straightforward task, once been through public hearing and approved by the government. The electronical reporting of geometry and descriptive data to the CDR is a bigger challenge, technically. Administrative areas, water bodies, monitoring and protected areas must be reported on a Geography Markup Language (GML) format and all the descriptive data on an Extensible Markup Language (XML) format. The electronically reported data represent the operationalization of the RBMPs and PoMs since all details cannot be contained in these. These data are used to control the fulfilment of the obligations and for statistical purposes by the European Environment Agency, which in addition uses these data in the production of maps, reports, and information to the public about the state of water.

The different timeline creates challenges especially in the reporting of exemptions, Article4(4). Because of this the EU Commission had to tailor the reporting tools to handle this different timeline. The reporting tool is a one-size-fits-all tool, so all data inserted into the reporting tables must be in line with the enumeration lists in the reporting guidance. A valid value for the EU countries is depending on previous choices in related tables would not be valid for the EEA/EFTA countries in the case of exemptions. In the second cycle the Commission interpreted the Norwegian data reported on the exemptions as a six-year delay, in other words, 2015 meant 2021. In the third cycle this is not possible since there is not an option for member states to use Article4(4) beyond 2027. The solution was agreed upon in a meeting with the Commission, to change the algorithm so the EEA/EFTA countries could report exemptions beyond 2027, and at the same time use the same reporting format as the member states. The CIS guidance was changed accordingly to this.

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Part 2. Assessment of cross-border anthropogenic pressure on groundwater state in the Polish-Ukrainian pilot area

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1. Review of EU guidelines

The assessment of cross-border anthropogenic pressure on groundwater state has been the object of interest of the EU for decades. One of the first documents containing important provisions on the monitoring and assessment of transboundary waters, the assessment of the effectiveness of measures taken to prevent, control and reduce transboundary impact, and the exchange of information on water and effluent monitoring was the Convention on the Protection and Use of Transboundary Watercourses and International Lakes (Helsinki, 1992).[1] The 1999 Protocol on Water and Health[2] under the Convention further addresses surveillance systems, early-warning systems for water-related disasters, integrated information systems, and the exchange of knowledge and experience.

In 2000 Guidelines on Monitoring and Assessment of Transboundary Groundwater[3] have been published however, they are strategic rather than technical character and intend to assist ECE governments and joint bodies in developing harmonised rules for the setting up and operation of systems for transboundary groundwater monitoring and assessment.

The character of these Guidelines is strategic rather than technical.

The EU legislation that aims to establish a framework for the protection and sustainable management of water resources is Water Framework Directive (2000/60/EC)[4]. It sets out objectives and measures to achieve good water status within the EU member states. To support its implementation the EU Member States have developed a common strategy that focuses on methodological questions related to common understanding of the technical and scientific implications of the WFD. The common grounds for the analysis of pressures and impacts on groundwater have been defined in the technical document entitled Common Implementation Strategy for the Water Framework Directive. Guidance document no 3. Analysis of Pressures and Impacts in 2003.[5]

The document not only sets the general approaches that can be taken according to water body type and data availability but also describes specific tools that consider one particular component of the process or environment and indicate ***what*** types of data may be useful in the analysis of impacts and pressures, ***why*** the data may be useful, and gives a ***European-scale source*** for the information, if one exists. In the current report the authors had decided to focus on the approaches dedicated to the groundwater as that is the primal object of interest of the EU-Waterres project.

[1] UN/ECE, 1992. Convention on the Protection and Use of Transboundary Watercourses and International Lakes
[2] UN/ECE, 1999. The Protocol on Water and health. Driving action on water, sanitation, hygiene and health
[3] UN/ECE Task Force on Monitoring and Assessment. Guidelines on Monitoring and Assessment of Transboundary Groundwaters
[4] Directive 2000/60/EC of the European Parliament and the Council of 23 October 2000 establishing a framework for Community action in the field of water policy
[5] EC, 2003. Common Implementation Strategy for the Water Framework Directive. Guidance document no 3. Analysis of Pressures and Impacts in 2003

1.1. Pressures and impacts on groundwater

Three objectives related to groundwater management can be outlined. Firstly, the aim is to implement measures that prevent or minimize the introduction of pollutants into groundwater, ensuring that the quality and quantity of groundwater do not deteriorate. Groundwater status is determined by its qualitative and chemical aspects, with the overall status considered to be poorer of the two.

Secondly, the goal is to protect, improve and restore all groundwater bodies while maintaining the balance between abstraction and recharge. The original objective of the WFD was to achieve good groundwater status by 2015 as specified in Annex V[6].

Thirdly, any significant and sustained increase in pollutant concentrations resulting from human activities must be reversed, progressively reducing pollution of groundwater.

In cases where groundwater is currently in good status but is at risk of becoming poor due to pressures, further characterization is required. It is important to note that a body with poor status is automatically considered to be at risk.

Article 17[7] of the WFD mandates the MS to propose a daughter directive specifically addressing groundwater. This directive is expected to define criteria for significant trends in pollutant concentrations and additional criteria for determining good groundwater chemical status. Furthermore, the daughter directive is expected to provide clarification on preventing or limiting the input of pollutants into groundwater as mentioned in the first objective.

Assessment of the impacts and pressures should be carried on in four steps:

1. The first step involves describing the driving forces, such as land use, urban development, industry, agriculture, and other activities that create pressures on the groundwater body, without considering their actual impacts.
2. The second step is to identify the pressures that may have impacts on the groundwater body and water uses. This includes assessing the magnitude of the pressures and the vulnerability of the groundwater body.
3. The third step entails evaluating the impacts resulting from the identified pressures.
4. The fourth step involves assessing the likelihood of failing of meeting the objectives.

In the initial assessment (for 2004), the focus was on identifying all potentially significant problems by listing pressures and assessing impacts on the groundwater body. This helped to identify areas where monitoring was needed to understand if the water body was at risk of not achieving the good status. The resulting list formed the basis for developing a program of measures to achieve the good status.

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[6] Directive 2000/60/EC of the European Parliament and the Council of 23 October 2000 establishing a framework for Community action in the field of water policy
[7] Ibid.

For the first stage, a screening approach is recommended to simplify the task of identifying pressures that may hinder the objectives. Member States (MS) should strive to provide the best estimate of significant pressures within the available time. Crosschecking estimates with the monitoring data and information on key drivers can improve confidence in the assessment.

The identification of significant pressures may involve a combination of monitoring data, modelling, and expert judgment. These pressures, along with groundwater bodies at risk of failing environmental objectives, need to be identified and reported in a practical and transparent manner that demonstrates Member States` decision-making process.

1.2. Identification of driving forces and pressures

The driving forces (DF) can be defined as the activities that generate pressures on groundwater bodies. DF can be quantified using aggregated data such as arable land area or population density. By comparing DF data with aggregated monitoring information, it becomes possible to assess the likelihood of DF being related to environmental pressures. This allows for a focused investigation into the expected pressures. The screening procedure allocates data collection and provides an independent assessment of pressure-impact relationships. Information on DF and pressures is necessary for both surface and groundwater bodies, as activities can impact multiple water bodies. Organizing data based on river basins or districts facilitates analysis, with the aid of GIS. The management of this information falls under the purview of the GIS Working Group.

A broad categorisation of pressures by DF has been given in Table 2.

Table 2. Categorisation of pressures by driving forces to be considered (After: Common Implementation Strategy for the Water Framework Directive (2000/60/EC), Guidance document no 3, Analysis of Pressures and Impacts)

Diffuse sources	• Urban drainage • Agriculture diffuse • Forestry • Other diffuse
Point source	• Waste water • Industry • Mining • Contaminated land • Agriculture point • Waste management • Aquaculture
Activities using specific substances	• Manufacture, use and emissions from all industrial / agricultural sectors
Abstraction	• Reduction in flow
Artificial recharge	• Groundwater recharge
Morphological	• Flow regulation • River management • Transnational and coastal management • Other morphological

Other anthropogenic	• Miscellaneous

1.3. Impact assessment

Assessing impacts on water bodies requires quantitative information about the state of the water body and the pressure acting on it. The analysis method depends on the available data, and a conceptual understanding of impact causation is essential. Simple models, such as conservative mixing models, may be suitable in some cases but may oversimplify the complexities of different catchment and water body types, interacting pressures, and data requirements.

Assessing impacts often involves hidden complexities. For example, evaluating the impact of groundwater abstraction requires considering the ecological status and flow requirements of associated surface water bodies, rather than relying solely on water balance model. While detailed numerical computer models of linked systems are possible, the necessary information is often lacking, making initial analyses based on available data and less demanding methods, like pressure screening tools, more practical.

When data is available for the water body itself, a direct impact assessment becomes possible, but constructing appropriate indicators is crucial. Many pressures do not have clear-cut impacts but change the probability of adverse conditions. For example, hydrological regime perturbations affect fish life intermittently, requiring estimation of the threshold at which changes in favourable conditions become threats to the ecosystem. Common hydrological indicators are insufficient, and specific calculations based on daily discharge statistics and expert opinion may be necessary.

Assessing water quality also presents challenges, as meaningful comparisons require considering the internal structure of data to account for normal variability. Sophisticated statistical techniques that account for seasonal and hydrologic components can facilitate comparisons between short-term data sets. However, these techniques may be unfamiliar to the European water experts. Overall, a nuanced understanding of impacts, appropriate indicator construction, and advanced statistical analyses are crucial for accurate assessments in water management.

The WFD sets objectives for individual pollutants in water bodies, and a three-stage approach is recommended to address pollution at different scales. At the European level, "priority substances" listed in Annex X[8] are of particular concern and their risk of failing objectives should be investigated for all water bodies. At the river basin level, a list of "relevant pollutants for a river basin" can be established, considering substances likely to pose a risk to objectives in multiple water bodies and potentially affecting downstream environments. At the sub-river basin and water body level, pollutants causing significant regional or local pressure may also need to be considered.

[8] Ibid.

Selecting relevant pollutants depends on significant pressures or impacts. Ideally, a clear relationship exists between a pollutant`s release, its occurrence and its effects on water bodies. However, data gaps exist for many pollutants, and only a limited number are regularly monitored. The analysis of pressures and impacts is the initial step towards identifying regulated pollutants under the WFD.

The establishment of a list of pollutants for analysis is followed by data collection on significant pressures and impacts. Environmental quality standards (EQS) are crucial benchmarks, representing the boundary between "good" and "average" status. Other objectives, such as deterioration, pollution reduction, and avoidance of downstream failures, also require assessment.

The list of relevant pollutants may evolve throughout the implementation of the WFD based on analysis and assessments. A transparent process linking the evolution of relevant pollutants to the WFD objectives is important. The term "discharge" is not clearly defined in the WFD, but a broad interpretation encompassing all sources and pathways into the aquatic environment is necessary.

Overall, a systematic approach and step-by-step approach is needed to identify and address pollutants that most significantly impact water bodies, considering the various levels and objectives outlined by the WFD.

1.4. Tools

The Guidance document no. 3 to the WFD[9] discusses also the tools necessary for conducting the general approach described above. It acknowledges that no single tool can perform a comprehensive pressure and impacts analysis for all types of water bodies. Instead, the guidance presents specific tools that focus on particular components of the process or environment, such as pressure assessment, surface water, groundwater and biology. It emphasizes the importance of selecting tools that are appropriate for the desired purpose, considering their capabilities and limitations.

The guidance highlights the value of local knowledge and experience in the analysis, suggesting that stakeholders should be involved to contribute complementary expertise. The pressure checklist containing a list of pressures to be considered during the assessment has been also provided. Additionally, screening techniques have been discussed as means to simplify the analysis process, particularly in the short-term implementation of the WFD.

The current state where required data and tools may not be fully available or identified has been also addressed. It focuses on identifying tools needed to address the specific questions by analysing the relationships between pressures, impacts, and the objectives of the WFD. Categorization of tools into three groups has been proposed:

1. Fully available tools with formalized rules or procedures,
2. Tools at a laboratory or pilot stage requiring further development,

[9] Op. cit. EC, 2003.

3. Non-existing tools that need research and development.

Annex V to the Guidance document no. 3. Analysis of pressures and impacts[10] provides detailed description of different types of tools identified within the general approach, including pressure screening and assessment, quantification of pollution pressures, tools for combining pressures with impact assessment (water body models), and impact assessment tools.

1.5. Data requirements

The Common Implementation Strategy for the Water Framework Directive discusses also the data requirements for conducting an analysis of impacts and pressures on water bodies. The data can be categorized into general descriptive information about the drainage basin and water bodies, data describing pressures, and data describing impacts. It has been stressed that national or regional datasets are likely to be the best source of information and data, therefore, it is not possible to provide a comprehensive list of such sources. Competent authorities are encouraged to be innovative in collecting data, including engaging stakeholders who may possess relevant records. The collected data should preferably be in digital form and used within a Geographic Information System.

The document specifies that certain sections of the analysis, such as characterization of surface water body types and ecoregions, should be completed prior to conducting the pressures and impacts analysis. It focuses on the sources of information relevant to the identification of pressures and assessment of impacts. The required data includes information about the water body, existing uses, and the state of the water body. Existing data should be primarily used, supplemented with new information as needed.

Different Member States possess varying types, sources, and amounts of information. Common categories of data include other EC Directives mentioned in the WFD Annex II, which provides information on specific pressures or environmental standards. National requirements, such as classification schemes and inventories mandated by national legislation, also contribute to the data.

1.6. Summary

The EU guidelines on the assessment of cross-border anthropogenic pressure on groundwater state provide a framework for evaluating the impact of human activities on groundwater quality across national boundaries. These guidelines aim to promote a harmonized approach among Member States in assessing and managing transboundary water resources.

The guidelines emphasize the importance of understanding the potential risks posed by anthropogenic pressures, such as pollution from industrial activities, agriculture, and urban development, on shared groundwater bodies. They highlight the need for cooperation and information exchange between neighbouring countries to effectively address the cross-border impacts.

[10] Ibid.

The assessment process involves several steps, including data collection, risk characterization and monitoring. Member States are encouraged to establish national databases and monitoring networks to ensure comprehensive understanding of groundwater quality and possible pressures. The guidelines also stress the importance of using standardized methods and criteria for assessing groundwater status and identifying trends.

Coordinated efforts and collaboration between Member States are essential for managing and mitigating cross-border impacts. The guidelines recommend establishing joint programs, sharing data and information, conducting joint assessments and implementing measures to address identified pressures. Regular reporting and review processes are also encouraged to monitor the effectiveness of implemented measures and facilitate adaptive management.

Overall, the guidelines provide a framework for assessing the impact of anthropogenic pressures on groundwater quality across national borders and promoting cooperation among Member States to ensure the sustainable management of shared groundwater resources.

2. Characteristics of transboundary layers and pressures on transboundary groundwater quantity and quality on individual sections of the Polish-Ukrainian border

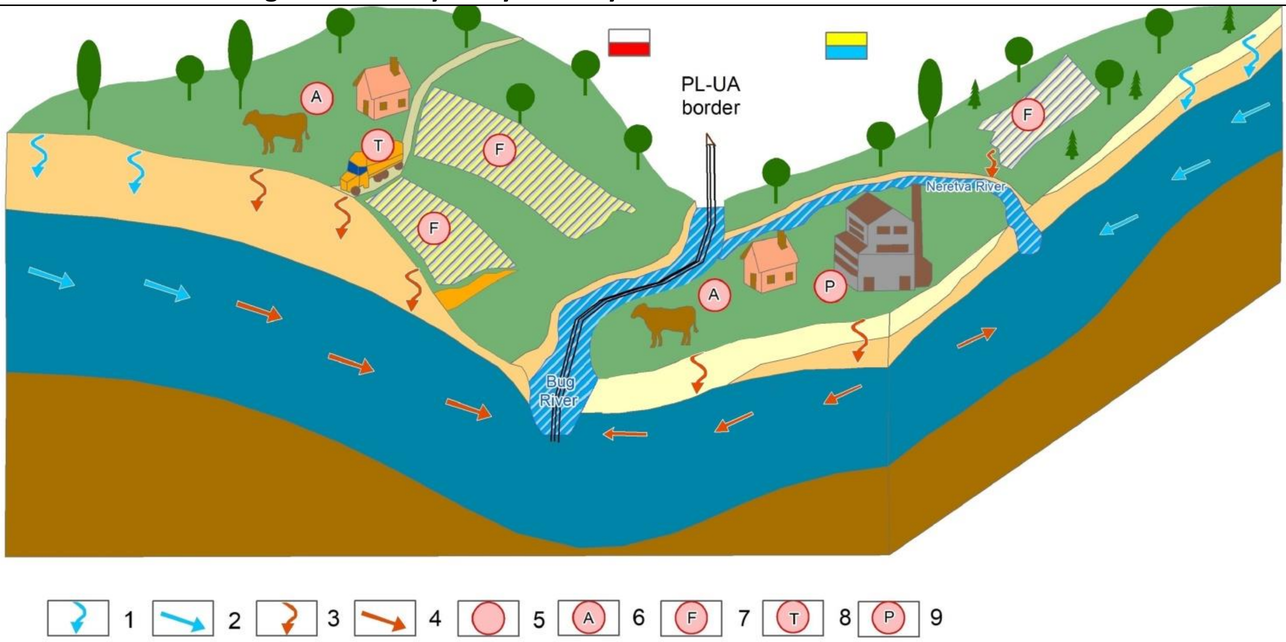
2.1. Section with the course of the Polish-Ukrainian border along the Bug River

Administrative location			
Poland		Ukraine	
County	Municipality	District	Territorial communities
Włodawski	Włodawa, Wyryki, Hańsk, Wola Uhruska, Urszulin, Stary Brus	Kovelskyi	Samarivska, Ratnivska, Zabolotivska, Zabrodivska, Dubechnenska, Shatska, Rivnenska, Holovnenska, Liubomlska, Vyshnivska
Łęczyński	Cyców	Volodymyr-Volynskyi	Ovadnivska, Ustyluzka, Volodymyr-Volynska, Poromivska, Novovolynska, Lytovezka, Ivanychivska, Zymnivska, Zaturtsivska, Lokachynska, Pavlivska
Parczewski	Sosnowica	Lutskyi	Horokhivska
Chełmski	Sawin, Ruda-Huta, Dorohusk, Chełm (city), Chełm, Wierzbica, Siedliszcze, Rejowiec Fabryczny, Rejowiec, Kamień, Żmudź, Leśniowice, Dubienka, Białopole, Wojsławice		
Hrubieszowski	Horodło, Hrubieszów (municipal commune) Hrubieszów, Uchanie, Trzeszczany, Werbkowice, Mircze,		

	Dołhobyczów		
Zamojski	Grabowiec, Miączyn, Sitno, Łabunie, Komarów-Osada,		
Tomaszowski	Tyszowce (municipal commune), Tyszowce		

Location map

Diagram of the hydrodynamic system on the Polish-Ukrainian border



1 – infiltration of unpolluted water,
2 – flow direction of unpolluted groundwater,
3 – seepage of polluted water,
4 – flow direction of polluted groundwater,
5-9 – types of pollution sources (A-Agriculture, F – Fertilizers, T – Transport, P – Municipal).

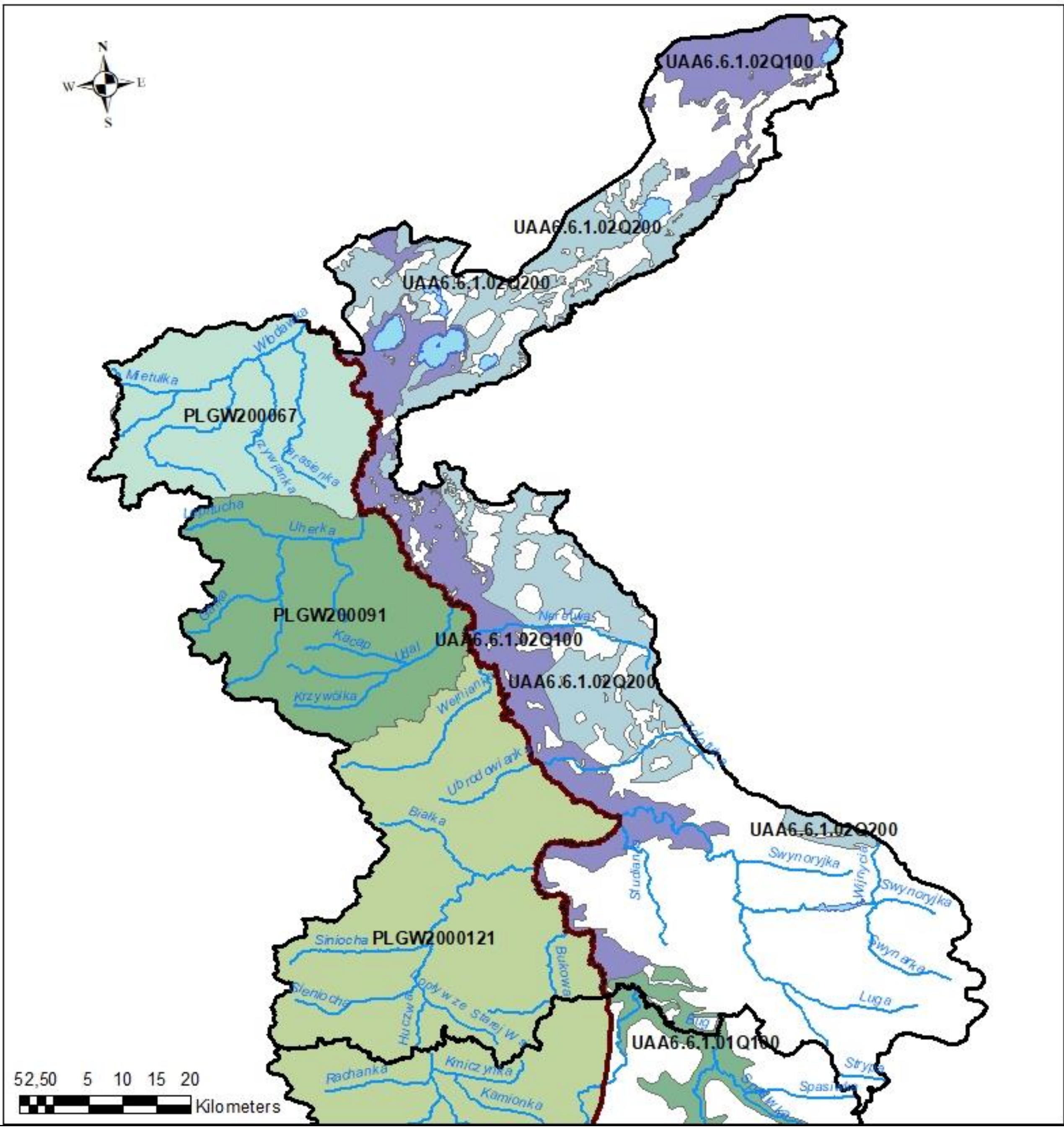
Physical-geographical region

Poland		Ukraine	
Province	Macroregion	Zone	Region
East Baltic-Belarusian Lowland	Volhynia Polesie	Polesia	Volhynia Polesie
Ukrainian Highlands	Volhynian Upland	Western Ukrainian	Volhynian Upland
Polish Highlands	Lublin Upland		

Main Rivers

Poland	Ukraine
Bug, Włodawka, Uherka, Udal, Wełnianka, Ubrodowianka, Huczwa, Bukowa	Bug, Neretva, Zolotukha, Luha, Studianka

Groundwater Bodies	
Poland	Ukraine
Quaternary GWB	
No: PLGW200067, PLGW200091, PLGW2000121	No: UAA6.6.1.02Q100, UAA6.6.1.02Q200



Upper Cretaceous GWB	
No: PLGW200067, PLGW200091, PLGW2000121	No: UAA6.6.1.01K100, UAA6.6.1.02K100

Land use

Poland		Ukraine	
% of anthropogenic areas	2,83	% of anthropogenic areas	3,72
% of agricultural areas	70,75	% of agricultural areas	53,89
% of forest and green areas	24,01	% of forest and green areas	35
% of wetlands	1,84	% of wetlands	5,05
% of water areas	0,57	% of water areas	2,34

Characteristics of transboundary aquifer			
Poland		Ukraine	
Q1 aquifer (Holocene, Pleistocene)	Lithology – sands, gravels; Type of aquifer – porous; Groundwater table type – unconfined; Depth to the aquifer – 1 - 22 m; Thickness of the aquifer - 2.3-62.7m	Q1 aquifer - UAA6.6.1.02Q100 (Holocene, Pleistocene)	Lithology - sand, gravel; Type of aquifer - porous; Groundwater table type - unconfined; Depth to the aquifer - 4-36 m; Thickness of the aquifer - 2.5-15.5 m
Q2 aquifer (Pleistocene)	Lithology – sands, gravels; Type of aquifer – porous; Groundwater table type – confined; Depth to the aquifer - 2-70 m; Thickness of the aquifer - 2-56.8 m	Q2 aquifer - UAA6.6.1.02Q200 (Pleistocene)	Lithology – sand, sandy loam, gravel; Type of aquifer - porous; Groundwater table type - unconfined; Depth to the aquifer - 1-30 m; Thickness of the aquifer - 6-17 m
Cr3 aquifer (Upper Cretaceous)	Lithology – limestone, marl; Type of aquifer – fractured; Groundwater table type – unconfined, partially confined; Depth to the aquifer - 0-70 m; Thickness of the aquifer - < 200 m	Cr3 aquifer - UAA6.6.1.01K100 (Upper Cretaceous)	Lithology – marl, rock, chalk, sandstone, limestone; Type of aquifer - fractured; Groundwater table type - confined; Depth to the aquifer - 7-82 m; Thickness of the aquifer - - 8-65 m
		Cr3 aquifer - UAA6.6.1.02K100 (Upper Cretaceous)	Lithology – marl, rock, chalk, sandstone, limestone; Type of aquifer - fractured; Groundwater table type - confined; Depth to the aquifer - 7-82 m; Thickness of the aquifer - 8-65 m

Scheme of water circulation

The structure of the aquifer system consists of two aquifers - Quaternary and Upper Cretaceous. These levels remain in very good hydraulic connectivity. The groundwater of both levels are recharged by rainwater infiltration and, under natural conditions, drained by surface watercourses. Locally, the Quaternary level is separated by hard-permeable formations with separation of Q1 and Q2. The Q1 surface level is not isolated from the ground surface, which enables its infiltration. The groundwater circulation system of the Q1 level is of a very local character. The Q2 level is recharged by seepage of water from the ground surface or from the Q1, Cr3 levels through hard-permeable formations and through hydrogeological windows from the adjacent aquifers. The Q2 level is drained by the main surface watercourses with deeply cut valleys: Bug, Krzna, Hanna, Włodawka, Luha. The Cr3 level is recharged by infiltration and locally by seepage from overlying aquifers. It is drained by the Bug River.

Hydrochemical types of groundwater			
HCO_3-Ca, HCO_3-SO_4-Ca, HCO_3-Ca-Mg			

Exploitation resources Q (m^3/h)			
Poland		Ukraine	
Q	284,5	Q	0
Cr	14282,4	Cr	1886,6
Q-Pg-Ng	36	Q-Pg-Ng	0
Q-Cr	361,1	Q-Cr	0
Pg-Ng-Cr	95	Pg-Ng-Cr	0

Quantitative resource pressures	
Poland	Ukraine
Depression cones related to the abstraction of groundwater and mining drainage in the area of Chełm from the Upper Cretaceous formations.	Local depression cones related to groundwater intake and mining drainage in the area of Novovolynsk.

Pollution pressures from diffuse sources	
Poland	Ukraine
Occurrence of areas susceptible to nitrate pollution from agriculture. Presence of urbanized areas with unregulated water and sewage management.	Occurrence of areas susceptible to nitrate pollution from agriculture. Significant share of urbanized areas with unregulated water and sewage management. Pollution of the territory during the exploitation of coal deposits.

Pollution pressures from point sources			
Poland		Ukraine	
Wastewater treatment plant	13	Wastewater treatment plant	8
Waste landfills	25	Waste landfills	40

Natural vulnerability to groundwater pollution			
Poland		Ukraine	
% very high	73,6	% very high	24,01
% high	18,32	% high	72,81
% average	8,02	% average	1,19
% low	0,06	% low	1,99
% very low	0	% very low	0
% no rating	0	% no rating	0

Groundwater risk from diffuse and point pollution sources			
Poland		Ukraine	
% very high	0,03	% very high	0,02
% high	0,8	% high	0,28
% average	0,03	% average	0,61
% low	71,81	% low	13,38
% very low	27,33	% very low	85,71
% no rating	0	% no rating	0

2.2. Section of the Polish-Ukrainian border within the southern fragment of the Bug river basin

Administrative location			
Poland		Ukraine	
County	Municipality	District	Territorial communities
Hrubieszowski	Dołhobyczów	Chervonohradskyi	Sokalska, Radekhivska, Chervonohradska, Belzka, Velykomostivska, Dobrotvirska
Tomaszowski	Krynice, Tarnawatka, Tomaszów Lubelski (city), Tomaszów Lubelski, Rachanie, Łaszczów (municipal commune), Łaszczów, Telatyn, Ulhówek, Jarczów, Lubycza Królewska, Bełżec	Lvivskyi	Rava-Ruska, Dobrosynsko-Maherivska, Zhovkivska, Kamianka-Buzka, Zhovtanetska, Kulykivska, Lvivska, Novoiarychivska, Murovanska, Pidberiztsivska, Davydivska, Bibrska, Peremyshlianska, Hlynianska
Lubaczowski	Narol, Horyniec-Zdrój	Zolochivskyi	Buska, Zolochivska, Zabolottsivska, Krasnenska
		Yavorivskyi	Yavorivska, Ivano-Frankivska

Location map

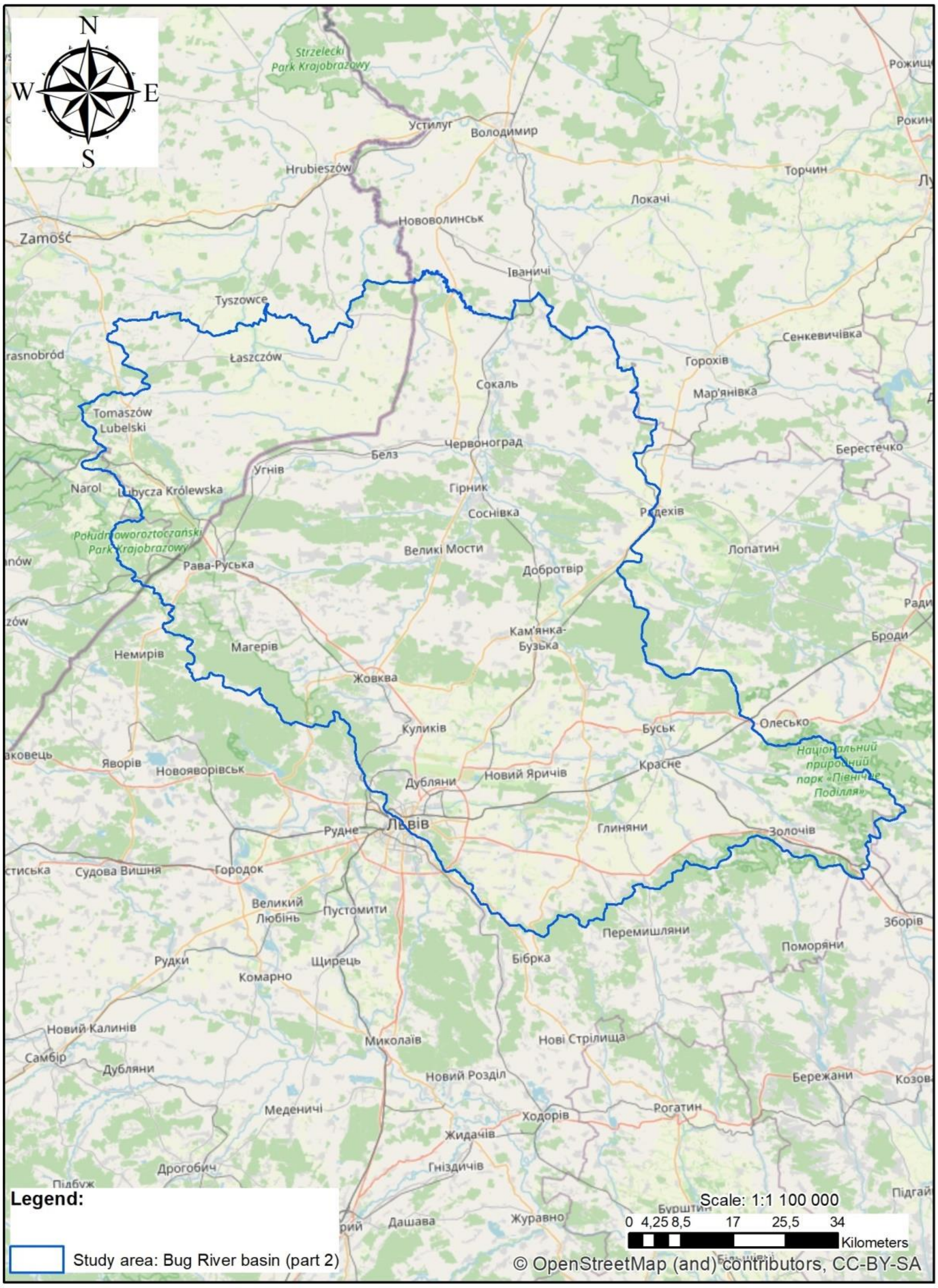
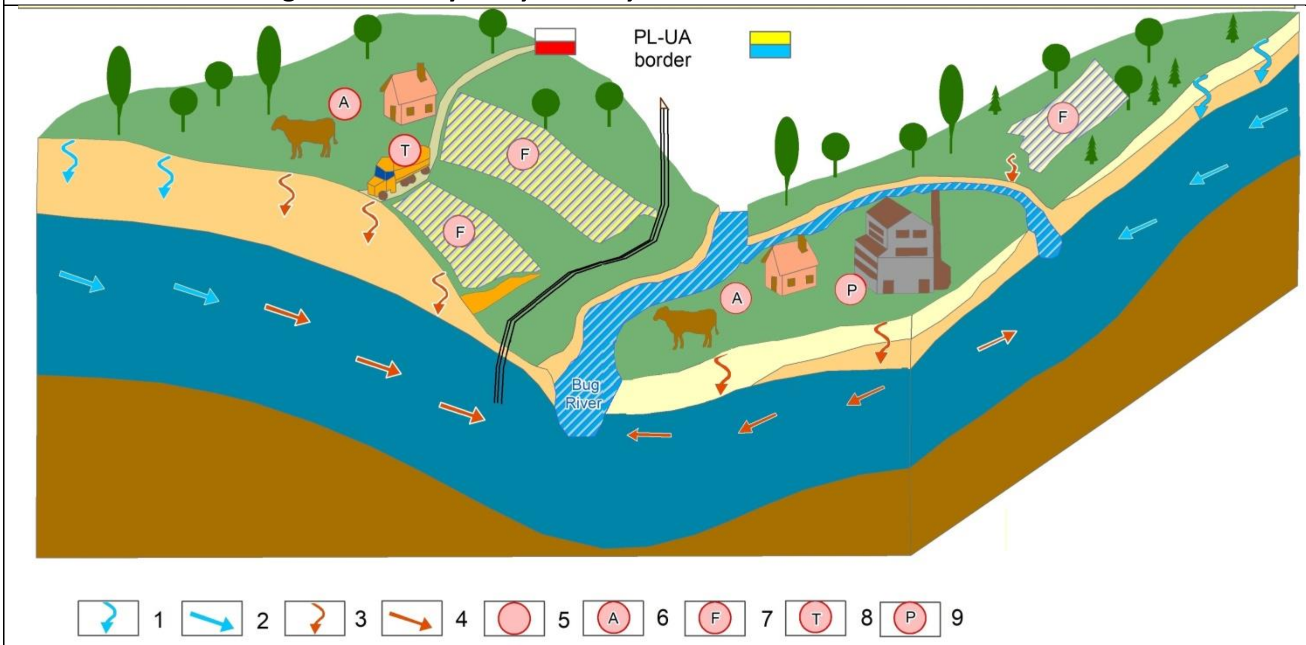


Diagram of the hydrodynamic system on the Polish-Ukrainian border



1 – infiltration of unpolluted water,
2 – flow direction of unpolluted groundwater,
3 – seepage of polluted water,
4 – flow direction of polluted groundwater,
5-9 – types of pollution sources (A-Agriculture, F – Fertilizers, T – Transport, P – Municipal).

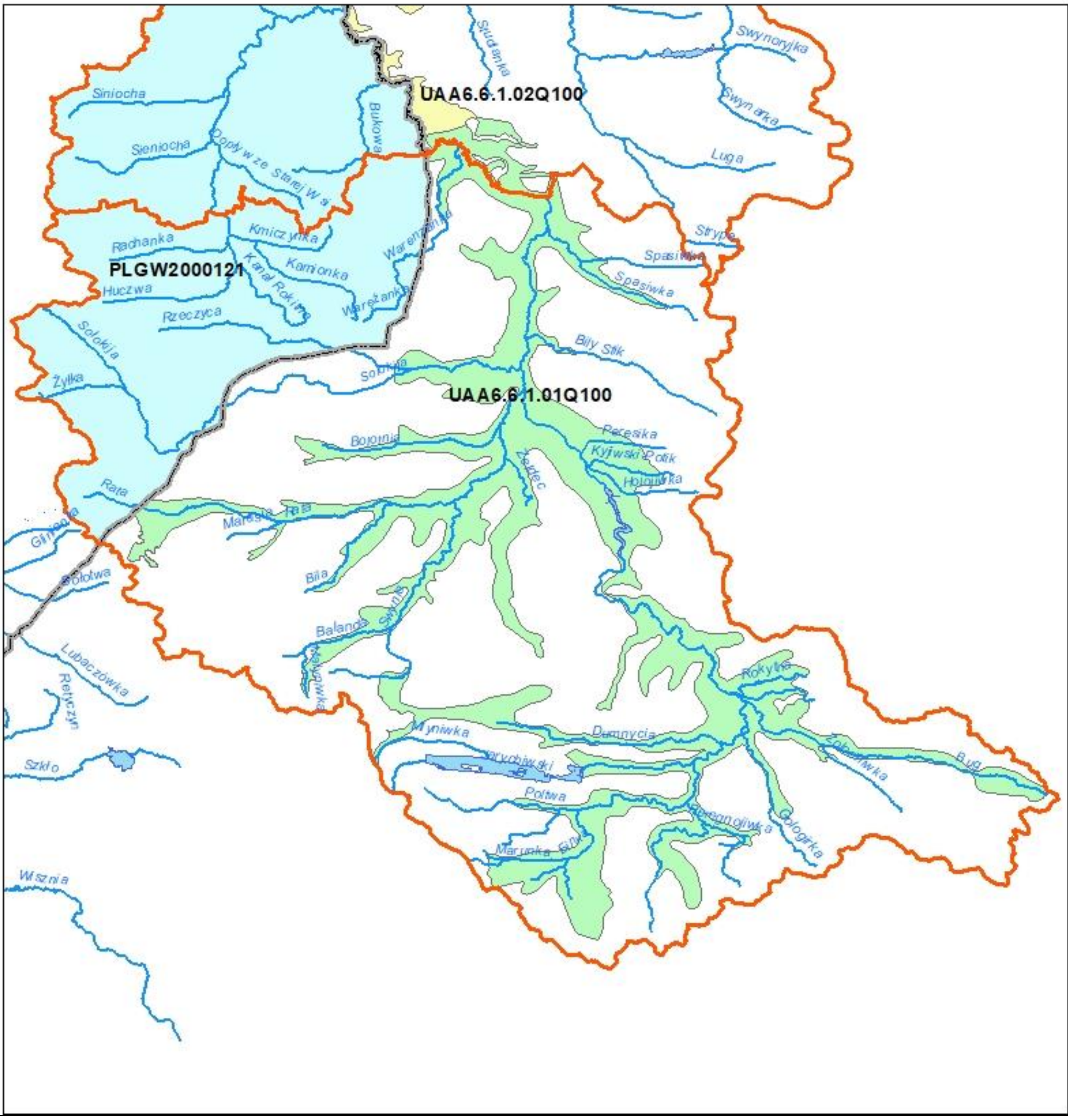
Physical-geographical region

Poland		Ukraine	
Province	Macroregion	Zone	Region
Ukrainian Highlands	Volhynian Upland Pobuże Basin	Western Ukraine	Little Polesie (Roztochia)
Polish Highlands	Roztochia		

Main Rivers

Poland	Ukraine
Huczwa, Sołokija, Rzeczyca, Warężanka, Rata	Bug, Sołokija, Svynia, Rata, Spasivka, Bilyi Stik, Poltva, Yarychivski

Groundwater Bodies	
Poland	Ukraine
Quaternary GWB	
No: PLGW2000121	No: UAA6.6.1.01Q100



Miocene GWB	
	No: UAA6.6.1.01N100

Upper Cretaceous GWB	
No: PLGW2000121	No: UAA6.6.1.01K100, UAA6.6.1.02K100

Devonian GWB	
	No: UAA6.6.1.01D100

Land Use

Poland		Ukraine	
% of anthropogenic areas	3,2	% of anthropogenic areas	6,81
% of agricultural areas	73,53	% of agricultural areas	60,97
% of forest and green areas	22,41	% of forest and green areas	29,49
% of wetlands	0,35	% of wetlands	2,29
% of water areas	0,51	% of water areas	0,44

Characteristics of transboundary aquifer			
Poland		Ukraine	
Q aquifer	Lithology - sands; Type of aquifer – porous; Groundwater table type – unconfined; Depth to the aquifer – 0,9 - 45 m; Thickness of the aquifer – 5,5-71,5m	Q aquifer - UAA6.6.1.01Q100 (Holocene, Pleistocene)	Lithology - sand, gravel, loam, sandy loam, peat; Type of aquifer - porous; Groundwater table type - unconfined; Depth to the aquifer - 4-36 m; Thickness of the aquifer - - 2,5-15,5 m
		N1 (N_1b_2+N_1b_3) aquifer - UAA6.6.1.01N100 (Miocene)	Lithology - organodetritic and sulphur-bearing limestones, sandstones, gypsums, gravels, sands; Type of aquifer - porous-fractured; Groundwater table type - confined; Depth to the aquifer - 3-35 m; Thickness of the aquifer - - 10-20 m
Cr3 aquifer (Upper Cretaceous)	Lithology – limestone, marl; Type of aquifer – fractured; Groundwater table type – confined; Depth to the aquifer - 0-1378 m; Thickness of the aquifer - 0.1-256 m	Cr3 aquifer - UAA6.6.1.01K100 (Upper Cretaceous)	Lithology - marls, chalk, gaize, spongiolites, clay limestones; Type of the aquifer - fractured; Groundwater table type - confined; Depth to the aquifer - 0,5-89 m; Thickness of the aquifer - 4,7-92,8 m
		Cr3 aquifer - UAA6.6.1.02Q200 (Upper Cretaceous)	Lithology - sandstones, mudstones, siltstones, limestones, dolomites; Type of the aquifer - fractured; Groundwater table type - confined; Depth to the aquifer – 73-270 m; Thickness of the aquifer - 45-100 m
		D3 aquifer - UAA6.6.1.01D100 (Upper Devonian)	Lithology - sand, gravel, loam, sandy loam, peat; Type of aquifer - porous; Groundwater table type -

			unconfined; Depth to the aquifer - 4-36 m; Thickness of the aquifer - - 2,5-15,5 m

Scheme of water circulation

The structure of the aquifer system consists of two aquifers - Quaternary and Upper Cretaceous. In the Ukrainian part, two more aquifers are additionally separated - Miocene and Upper Devonian. The waters of the Quaternary level are recharged by infiltration of rainwater and, under natural conditions, drained by surface watercourses. The Cr3 level is recharged by seepage from the overlying aquifers, and is drained by the Bug River. The active water capacity of the Upper Cretaceous formations is created by fissures and macropores and microcracks connecting with them. Groundwater circulation in Cr3 aquifer takes place through a system of interconnected fissures. The water table of Cr3 aquifer is mostly confined. In river valleys, where there are no formations insulating the Cretaceous level, it occurs in hydraulic connection with the Quaternary level. The Miocene level occurs on the Ukrainian side within the boundaries of the Carpathian Foredeep. As a usable aquifer, it is of local importance, because most of Foredeep is filled with thicker series of Kraków clays. The aquifers are composed of sandstones and limestone-lithomnium formations. The average thickness of these sediments is up to 30.0 m. These formations lie at a depth of 16-21 m and sink in a south-western direction. Groundwater table is confined, drilled at a depth of 11.0 - 46.0 m, it stabilizes at a depth of 5.0 - 13.0 m b.g.l. The presence of sulphate therapeutic waters is also associated with N1 aquifer. The N1 and Cr3 levels are in hydraulic contact.

Hydrochemical types of groundwater

HCO_3-Ca, HCO_3-SO_4-Ca, HCO_3-Ca-Mg

Exploitation resources Q (m^3/h)

Poland		Ukraine	
Q	0	Q	0
Pg-Ng	0	Ng	22,1
Cr	7694,9	Cr	11805,8
Q-Cr	75,0	Q-Cr	0
Pg-Ng-Cr	0	Ng-Cr	6

Quantitative resource pressures

Poland	Ukraine
Local depression cones associated with groundwater abstraction.	Depression cones (regional-local depression cones) related to the abstraction of groundwater, mining drainage in the Chervonohrad region, the influence of the Lviv and Sokalsko-Chervonohrad agglomerations.

Pollution pressures from diffuse sources

Poland	Ukraine
Presence of urbanized areas with unregulated water and sewage management.	Occurrence of areas susceptible to nitrate pollution from agriculture. Significant share of urbanized areas with unregulated water and sewage management. The influence of the Lviv agglomeration. Pollution of the territory during the exploitation of coal deposits.

Pollution pressures from point sources			
Poland		Ukraine	
Wastewater treatment plant	6	Wastewater treatment plant	25
Waste landfills	9	Waste landfills	21

Natural vulnerability to groundwater pollution			
Poland		Ukraine	
% very high	76,19	% very high	19,92
% high	19,44	% high	52,39
% average	4,22	% average	19,17
% low	0	% low	3,93
% very low	0	% very low	4,59
% no rating	0,15	% no rating	0

Groundwater risk from diffuse and point pollution sources			
Poland		Ukraine	
% very high	0	% very high	0,17
% high	0,67	% high	0,77
% average	0,23	% average	0,23
% low	72,12	% low	98,83
% very low	26,83	% very low	0
% no rating	0,15	% no rating	0

2.3. Section of the Polish-Ukrainian border within the northern (pre-Carpathian) part of the San river basin

Administrative location			
Poland		Ukraine	
County	Municipality	District	Territorial communities
Lubaczowski	Lubaczów (municipal commune), Lubaczów, Horyniec-Zdrój, Cieszanów, Oleszyce (municipal commune), Oleszyce, Stary Dzików, Wielkie Oczy,	Lviv	Rava-Ruska, Velykoliubinska, Horodotska
Jarosławski	Wiązownica, Laszki, Radymno	Sambir	Dobromylska, Biskovytska, Rudkivska, Khyrivska
Przeworski	Adamówka, Sieniawa	Yavoriv	Novoiavorivska, Mostyska, Yavorivska, Sudovovyshnianska, Shehynivska
Przemyski	Stubno, Medyka, Żurawica, Przemyśl (city), Przemyśl, Fredropol, Bircza		
Bieszczadzki	Ustrzyki Dolne		

Location map

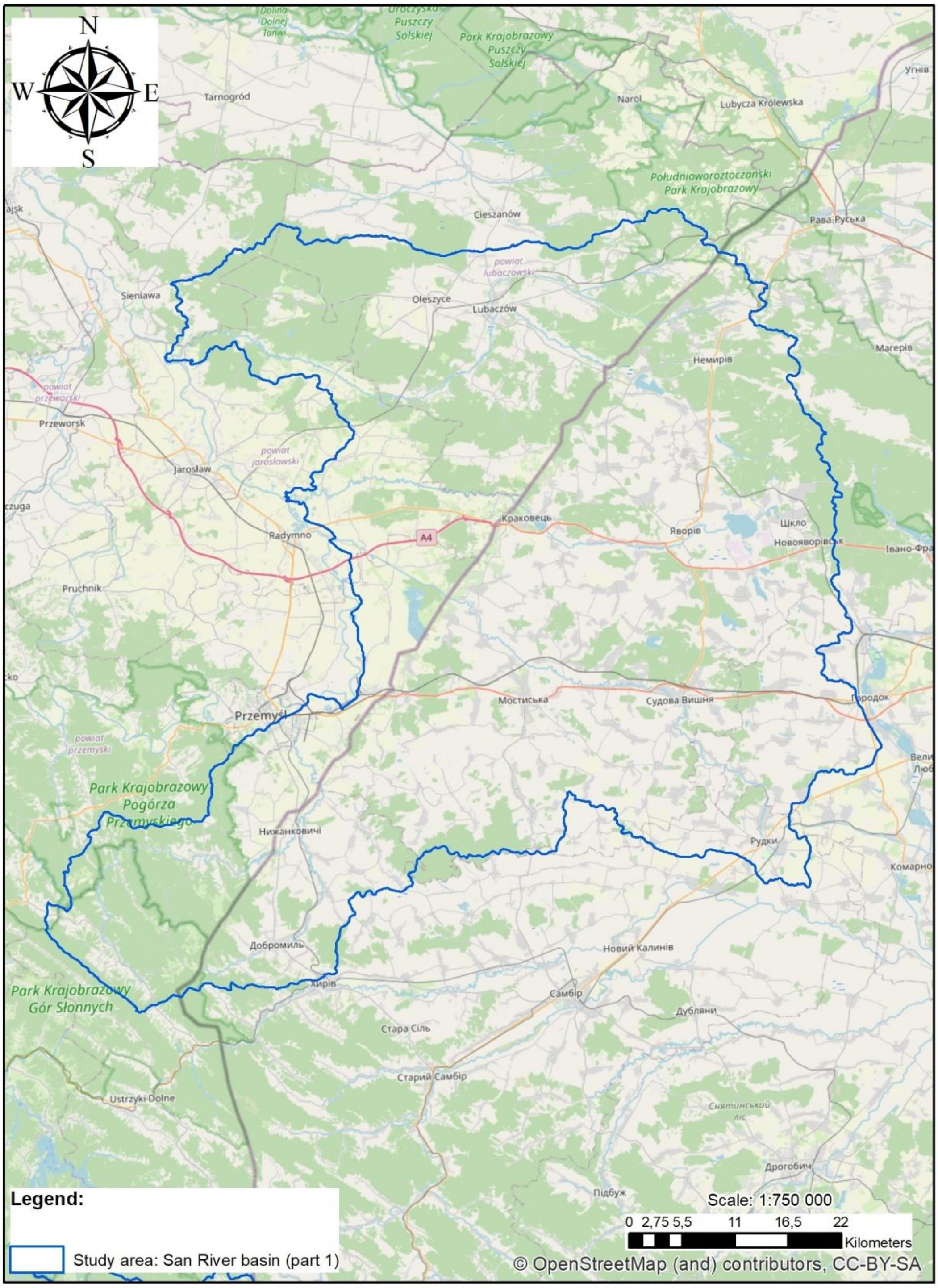
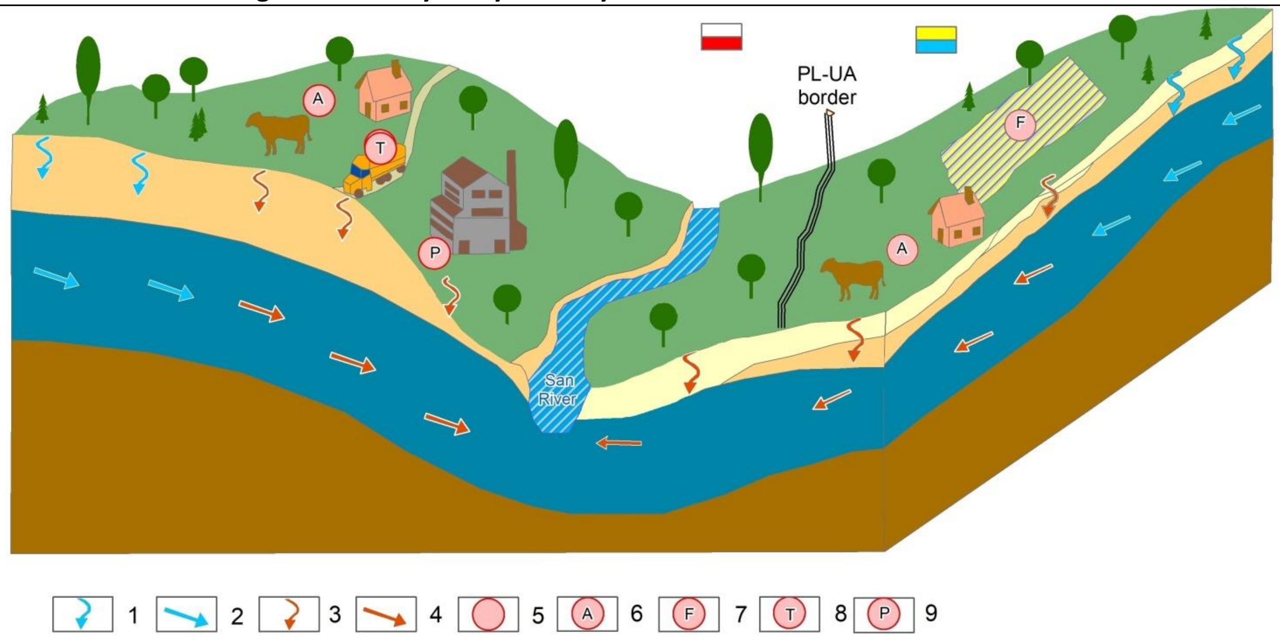


Diagram of the hydrodynamic system on the Polish-Ukrainian border



1 – infiltration of unpolluted water,
2 – flow direction of unpolluted groundwater,
3 – seepage of polluted water,
4 – flow direction of polluted groundwater,
5-9 – types of pollution sources (A-Agriculture, F – Fertilizers, T – Transport, P – Municipal).

Physical-geographical region

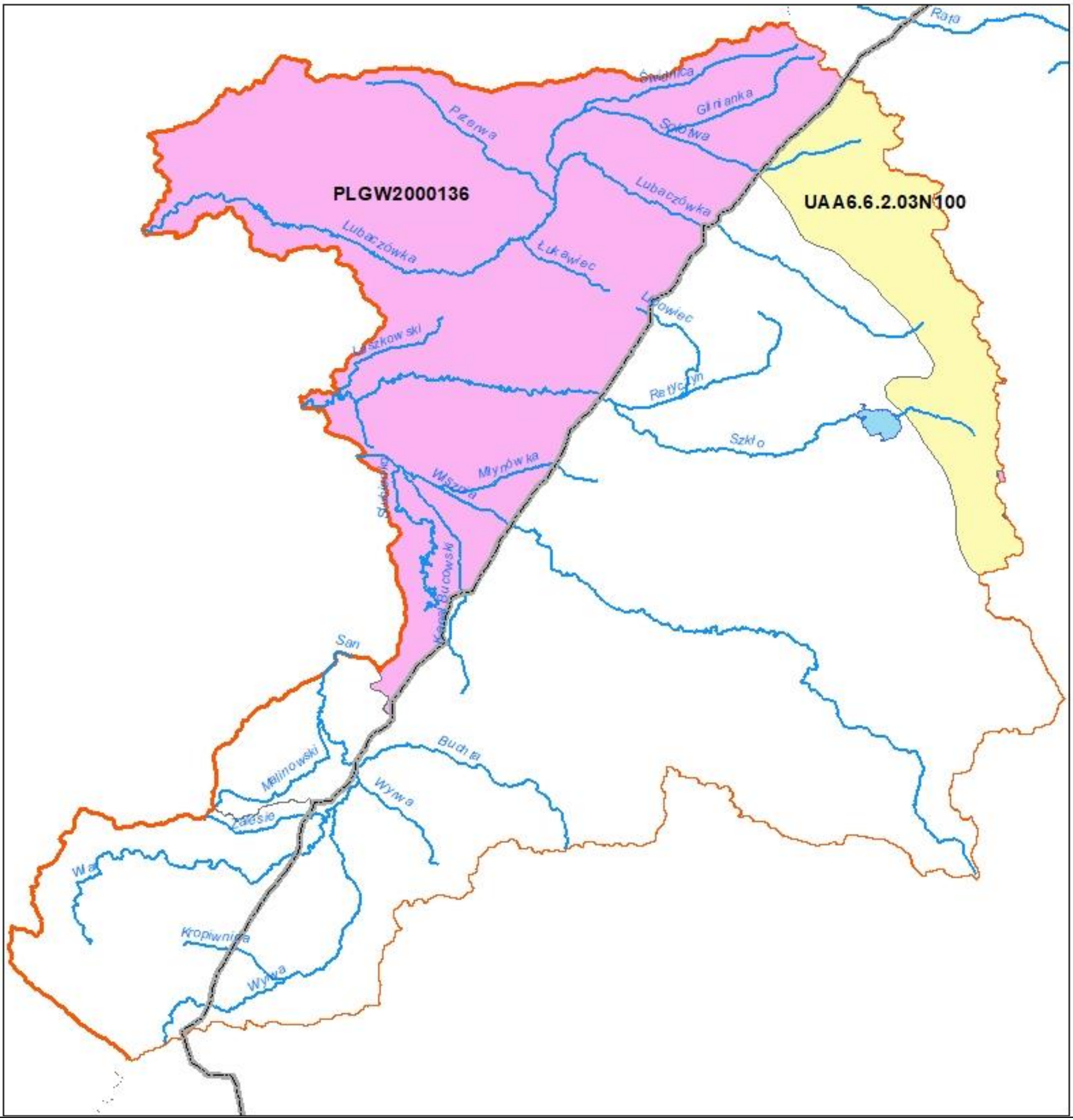
Poland		Ukraine	
Province	Macroregion	Zone	Region
Polish Highlands	Roztochia	Western Ukrainian	Roztocko-Opilski
Western Carpathians with Western and Northern Subcarpathia	Sandomierz Valley, Central Beskidian Piedmont	Ukrainian Carpathians	Carpathian Upland, Outer Carpathians
Easterm Carpathians with Eastern Subcarpathia	Sand – Dniester Plateau, Wooded Carpathians		

Main Rivers

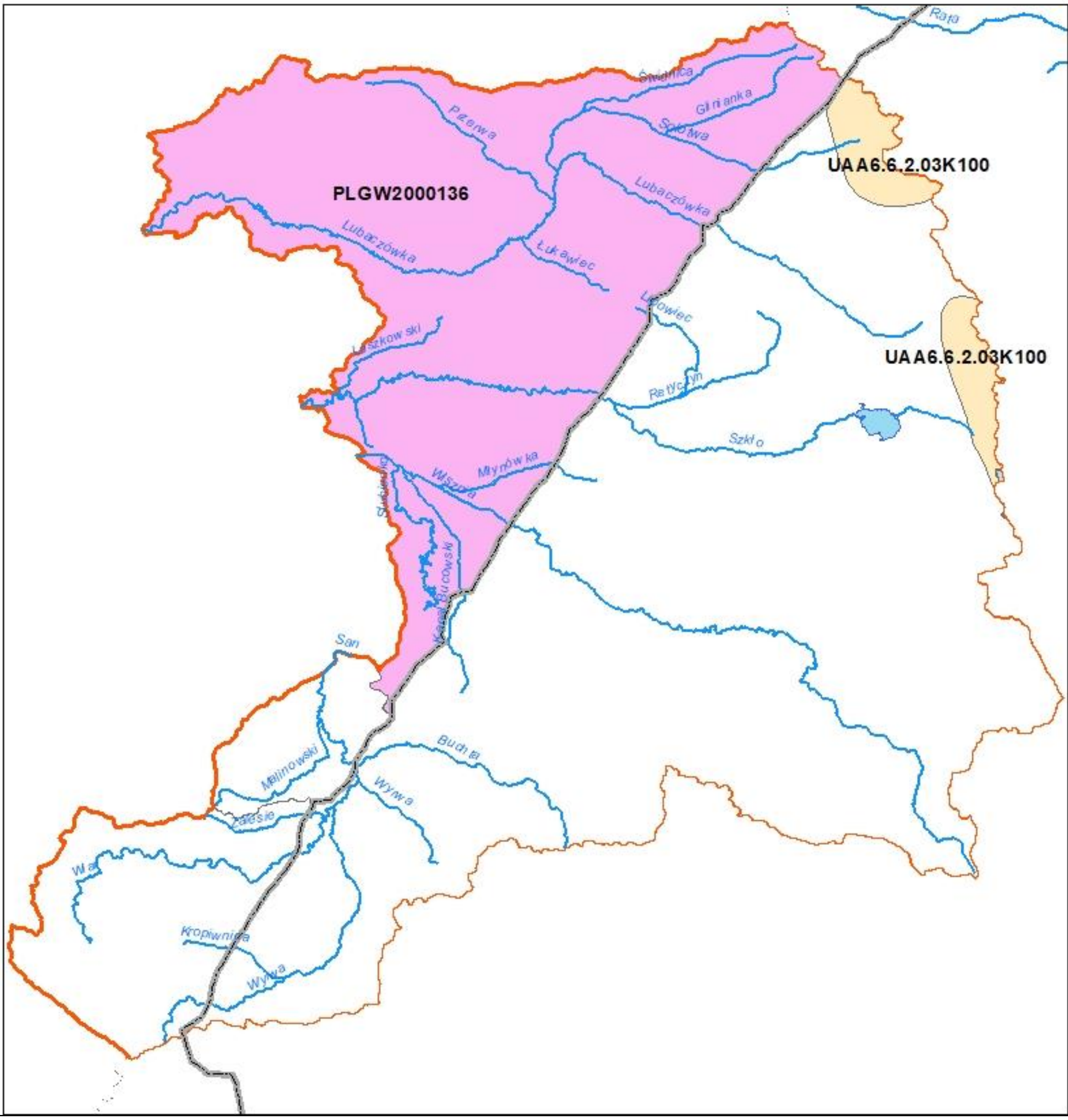
Poland	Ukraine
San, Lubaczówka, Szkło, Wisznia, Wiar, Wyrwa	Lubaczówka, Szkło, Retychin, Wisznia, Wiar, Wyrwa, Bukhta

Groundwater Bodies	
Poland	Ukraine
Quaternary GWB	
No: PLGW2000136, PLGW2000154, PLGW2000168	No: UAA6.6.2.03Q100, UAA6.6.2.03Q200

Miocene GWB	
No: PLGW2000136	No: UAA6.6.2.03N100



Upper Cretaceous GWB	
No: PLGW2000136	No: UAA6.6.2.03K100



Land use

Poland		Ukraine	
% of anthropogenic areas	3,42	% of anthropogenic areas	10,25
% of agricultural areas	45,65	% of agricultural areas	54,72
% of forest and green areas	49,94	% of forest and green areas	32,95
% of wetlands	0,39	% of wetlands	1
% of water areas	0,6	% of water areas	1,08

Characteristics of transboundary aquifer			
Poland		Ukraine	
Q aquifer	Litology – sands, gravel, peables; Type of the aquifer – porous; Groundwater table type – unconfined, locally confined; Depth to the aquifer – up to 48 m; Thickness of the aquifer – up to 20 m	Q aquifer - UAA6.6.2.03Q100 (Holocene, Pleistocene)	Lithology – sands, gravel; Type of the aquifer – porous; Character of the aquifer - unconfined; Depth to the aquifer – 2-18 m; Thickness of the aquifer - 4-16 m
		Q2 aquifer - UAA6.6.2.03Q200 (Pleistocene)	Lithology – sands, sandy loams, loams; Type of the aquifer – porous; Character of the aquifer - unconfined; Depth of the aquifer – 1-15 m; Thickness of the aquifer - 6-20 m
Pg-Ng (Paleogene-Neogene) aquifer (covers a small area in the northern part)	Lithology – sands, sandstones, limestone-lithomnium formations; Type of the aquifer – porous; Groundwater table type – confined; Depth to the aquifer – 16-300 m; Thickness of the aquifer – up to 30 m	N1 (N_1b_2+N_1b_3) aquifer - UAA6.6.2.03N100 (Miocene)	Lithology – organodetritic and sulphur-bearing limestones, sandstones, gypsums, gravels, and sands; Type of the aquifer – fractured; Character of the aquifer - confined; Depth of the aquifer – 2-30 m; Thickness of the aquifer - 30-50 m
Cr3 aquifer (covers a small area in the northern part)	Lithology – marls, gaize, limestones; Type of the aquifer – fractured; Groundwater table type – unconfined, locally confined; Depth to the aquifer – b.d. m; Thickness of the aquifer – 100 m (on average)	Cr3 aquifer - UAA6.6.2.03K100 (Upper Cretaceous)	Lithology – Marls, chalk, gaize, spongiolites, clay limestones; Type of the aquifer – fractured; Groundwater table type - confined; Depth to the aquifer – 0,5-80 m; Thickness of the aquifer - 7-53 m
Pg-Cr (flysch) aquifer (Paleogene-Cretaceous)	Lithology – sandstones, shales; Type of the aquifer – fractured – porous; Groundwater table type – unconfined;	Pg-Cr (flysch) aquifer (Paleogene-Cretaceous)	Lithology – sandstones, argillites; Type of the aquifer – porous- fractured; Groundwater table type -

	Depth to the aquifer – 0,7-64 m; Thickness of the aquifer – 0,6-82,6 m		unconfined; Depth to the aquifer – 0,3-6 m; Thickness of the aquifer – no data

Scheme of water circulation

The groundwater circulation system is largely shaped by the San River and its tributaries. In most parts of the area, water circulation takes place only in Quaternary formations, and these spread only in the areas of current and burried river valleys and are related to the range of occurrence of sandy fluvioglacial formations. Surface recharge is provided by atmospheric precipitation. Precipitation directly feeds the Q aquifer. If recharge does not reach the San or one of its tributaries, the Paleogene - Neogene - Cretaceous level recharged by the seepage from the Q aquifer in places where they are directly one below the other. Only in the region north of Przemyśl, where the overburden of the Quaternary level is over 10 m thick, the clay layer is very difficult or practically non-existent (Żurawica area). The direction of water flow in the Quaternary level, especially within river valleys, is determined by watercourses that are of draining character in this area. Recharge areas within the discussed unit are outcrops of permeable rocks: various types of sands. The deeper Palaeogene-Neogene-Cretaceous aquifer has quite limited contact with the surface through which direct atmospheric recharge could take place. In this situation, recharge takes place without major obstacles through the Quaternary aquifer, most often formed in the form of various types of sand and occurring directly above. In the Paleogene-Neogene and Cretaceous carbonate systems, waters circulate mainly in a system of fractures, and the depth range of the occurrence of patent fractures cannot be too deep, as it is assumed to be up to about 120 meters. Within the Miocene formations, there are interbeddings of considerable size with saline waters with mineralization associated with sulphur deposits also present in these sediments. Paleogeomorphological forms in which the privileged flow of water takes place are also found in the described area of the burried valley, especially the one in Biłgoraj-Lubaczów. In the case of the flysch layer, due to the varied relief and large slopes of the terrain, surface runoff plays an important role, and recharge occurs primarily in early spring through direct infiltration of water from the melting snow cover. For the flysch aquifer, the areas of the most intensive groundwater recharge are the higher parts of the terrain, and the drainage zones are river valleys. Within the flysch aquifer, groundwater flow is possible only in the zone of active water exchange and takes place in accordance with the morphology of the area. Deeply cut streams, which are tributaries of the San and Wiar, drain both Quaternary aquifer (alluvium) and flysch aquifer. Faults and dislocation zones play an important role in the circulation of groundwater. They are associated with zones of increased groundwater drainage, manifested in the presence of sources with a greater discharge. Due to the morphology of the terrain and the shallow impermeable substrate (the permeable zone reaches a maximum depth of 60-80 m), it is not possible to develop other than local circulation systems.

Hydrochemical types of groundwater

HCO_3-Ca, HCO_3-SO_4-Ca, HCO_3-Ca-Mg, HCO_3-SO_4-Ca-Mg, HCO_3-Na, HCO_3-Na-Ca

Exploitation resources Q (m^3/h)

Poland		Ukraine	
Q	3062,7	Q	40,7
Pg-Ng	30	Ng	1224,4
Cr	91,4	Cr	10,3
Q-Pg-Ng	0	Q-Pg-Ng	219
Pg-Ng-Cr	0	Pg-Ng-Cr	1,9

Quantitative resource pressures	
Poland	Ukraine
None	Depression cones related to the abstraction of groundwater in the municipal sector (mainly intakes supplying the Lviv agglomeration) and medicinal (sanitary intakes exploiting the Miocene level)

Pollution pressures from diffuse sources	
Poland	Ukraine
Presence of urbanized areas with unregulated water and sewage management.	Occurrence of areas susceptible to nitrate pollution from agriculture. Significant share of urbanized areas with unregulated water and sewage management. The influence of the Lviv agglomeration. Unreclaimed areas after sulphur extraction - Yavoriv, Nemyriv.

Pollution pressures from point sources			
Poland		Ukraine	
Wastewater treatment plant	7	Wastewater treatment plant	15
Waste landfills	9	Waste landfills	5

Natural vulnerability to groundwater pollution			
Poland		Ukraine	
% very high	59,66	% very high	28,88
% high	0,24	% high	0,02
% average	0	% average	0
% low	0	% low	0,73
% very low	0	% very low	20,92
% no rating	40,1	% no rating	49,45

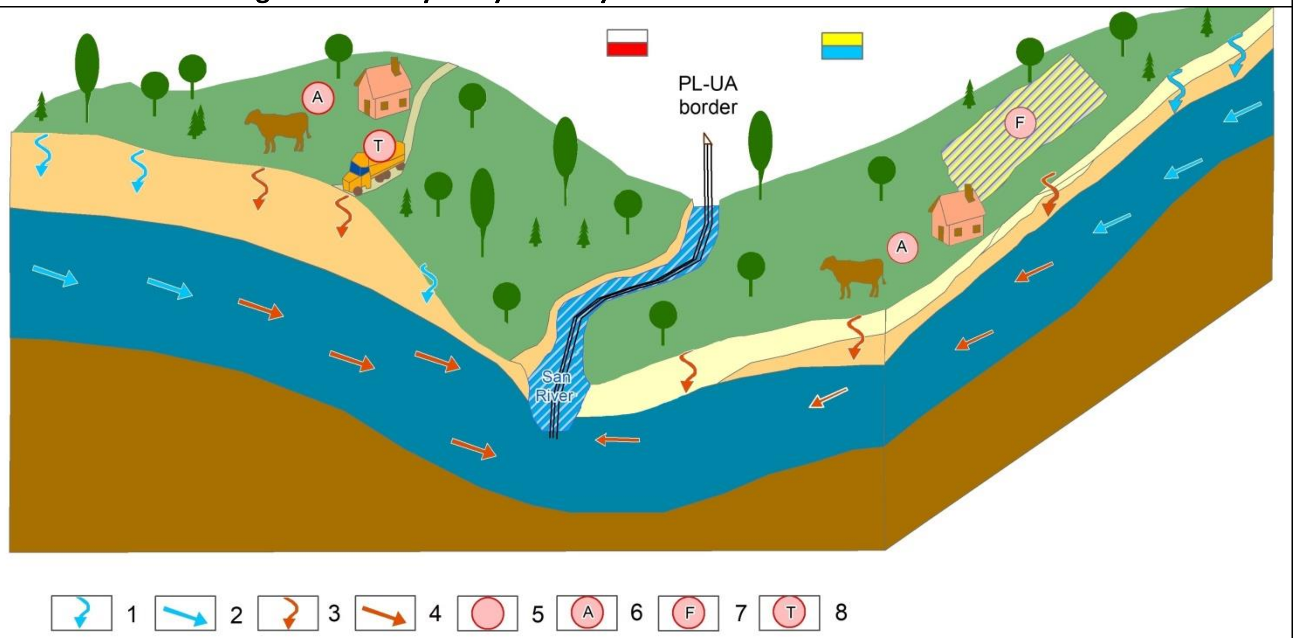
Groundwater risk from diffuse and point pollution sources			
Poland		Ukraine	
% very high	0,06	% very high	0,17
% high	0,48	% high	0,09
% average	0	% average	0,09
% low	31,85	% low	22,69
% very low	26,91	% very low	27,51
% no record	40,7	% no record	49,45

2.4. A section of the Polish-Ukrainian border within the southern (Carpathian) part of the San river basin

Administrative location			
Poland		Ukraine	
County	Municipality	District	Territorial communities
Bieszczadzki	Lutowiska, Czarna	Sambir	Turkivska, Borynska
Leski	Solina		

Location map


Diagram of the hydrodynamic system on the Polish-Ukrainian border



1 – infiltration of unpolluted water,
2 – flow direction of unpolluted groundwater,
3 – seepage of polluted water,
4 – flow direction of polluted groundwater,
5-9 – types of pollution sources (A-Agriculture, F – Fertilizers, T – Transport, P – Municipal).

Physical-geographical region

Poland		Ukraine	
Province	Macroregion	Zone	Region
Eastern Carpathians with Eastern Subcarpathia	Wooded Carpathians	Ukrainian Carpathians	Outer Carpathians

Main Rivers

Poland	Ukraine
San, Wołosaty	San, Rika

Groundwater Bodies	
Poland	Ukraine
No: PLGW2000168	None

Land use

Poland		Ukraine	
% of anthropogenic areas	0,78	% of anthropogenic areas	4,76
% of agricultural areas	9,19	% of agricultural areas	32,29
% of forest and green areas	89,61	% of forest and green areas	62,91
% of wetlands	0,01	% of wetlands	0
% of water areas	0,41	% of water areas	0,04

Characteristics of transboundary aquifer			
Poland		Ukraine	
Q aquifer (covers a small area in the northern part)	Lithology – sands, gravels, peables; Type of aquifer – porous; Groundwater table type – unconfined, locally confined; Depth to the aquifer – 0,5-5,1 m; Thickness of the aquifer – 0,9-11,6 m	Q aquifer (covers a small area in the northern part) (Holocene)	Lithology – boulders, pebbles, sands, clay sands; Type of aquifer – porous; Character of the aquifer - unconfined; Depth to the aquifer – 0 -5 m; Thickness of the aquifer – no data
Pg-Cr (flysch) aquifer (Paleogene-Cretaceous)	Lithology – sandstones, shales; Type of aquifer – fractured - porous; Groundwater table type – confined; Depth to the aquifer – 0,7-64 m; Thickness of the aquifer – 0,6-82,6 m	Pg-Cr (flysch) aquifer (Paleogene-Cretaceous)	Lithology – sandstones, argillites; Type of aquifer – porous-fractured; Groundwater table type - unconfined; Depth to the aquifer – 0,3-6 m; Thickness of the aquifer – no data

Scheme of water circulation
Groundwater is recharged mainly by direct infiltration of atmospheric precipitation and, to a small extent, by infiltration of surface water and inflow from the ground. The supply of the flysch layer depends mainly on the lithological character of the weathered substrate and the angle of slope inclination. The most favorable conditions for infiltration exist within river valleys and valleys. Groundwater flows towards river valleys, which are the basis of drainage, however, for deeper aquifers it is mainly the San River. Groundwater circulation directions are often complicated due to the lithology and tectonics of the Carpathian flysch formations. Generally, waters of all aquifers flow towards natural drainage zones.

Hydrochemical types of groundwater
HCO_3-Ca, HCO_3-SO_4-Ca, HCO_3-Ca-Mg, HCO_3-SO4-Ca-Mg, HCO_3-Na, HCO_3-Na-Ca

Exploitation resources Q (m^3/h)			
Poland		Ukraine	
Pg-Ng	30	Pg-Ng	0

Quantitative resource pressures	
Poland	Ukraine
None	None

Pollution pressures from diffuse sources	
Poland	Ukraine
None	None

Pollution pressures from point sources			
Poland		Ukraine	
Wastewater treatment plant	0	Wastewater treatment plant	0
Waste landfills	1	Waste landfills	0

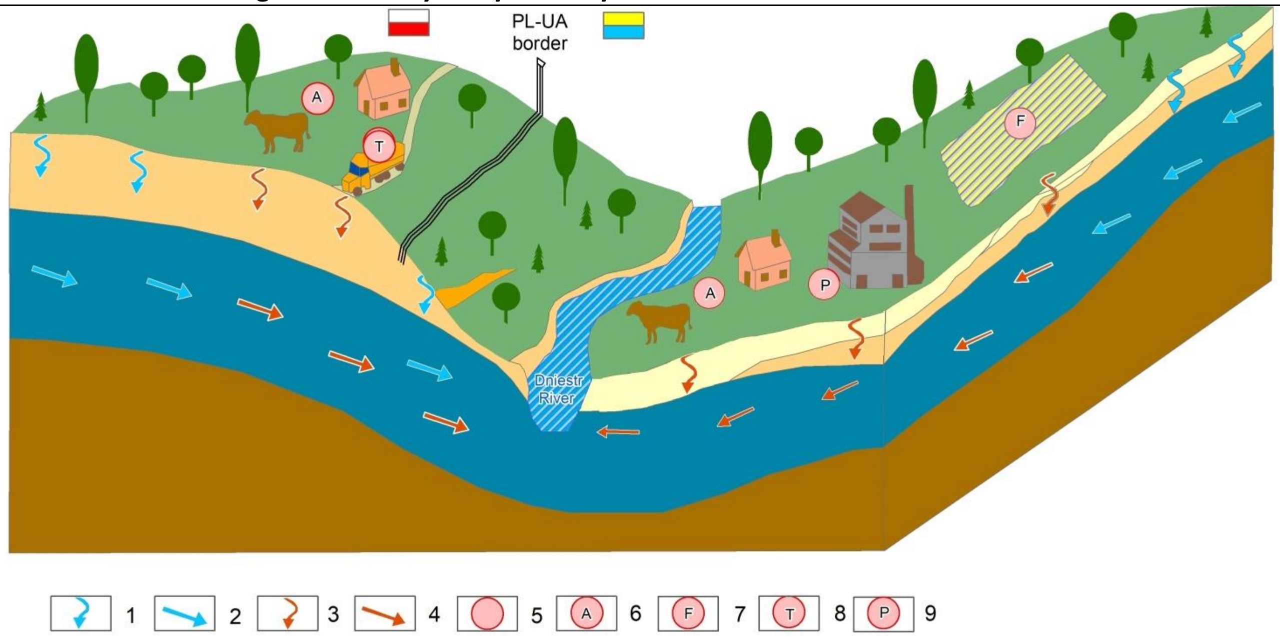
Natural vulnerability to groundwater pollution			
Poland		Ukraine	
% very high	54,26	% very high	9,65
% high	0	% high	0
% average	0	% average	0
% low	0	% low	0
% very low	0	% very low	0
% no rating	45,74	% no rating	90,35
Groundwater risk from diffuse and point pollution sources			
Poland		Ukraine	
% very high	0	% very high	0
% high	0	% high	0
% average	0	% average	0
% low	3,57	% low	0
% very low	49,24	% very low	0
% no rating	47,19	% no rating	100

2.5. A section of the Polish-Ukrainian border within the catchment area of the Dniester River

Administrative location			
Poland		Ukraine	
County	Municipality	District	Territorial communities
Bieszczadzki	Ustrzyki Dolne (city), Ustrzyki Dolne, Czarna	Drohobychskyi	Medenytska, Skhidnytska, Truskavetska, Drohobytska, Boryslavska
		Lvivskyi	Bibrska, Obroshynska, Zymnovodivska, Shchyretska, Komarnivska, Sokilnytska, Zhovkivska, Pustomytivska, Velykoliubinska, Lvivska, Davydivska, Solonkivska, Horodotska
		Sambirskyi	Biskovytska, Ralivska, Sambirska, Starosambirska, Rudkivska, Turkivska, Novokalynivska, Strilkivska, Novokalynivska, Borynska, Khyrivska, Dobromylska
		Stryishyi	Trostianetska, Stryiska, Novorozdilska, Skolivska, Khodorivska, Zhydachivska, Hrabovetsko-Dulibivska, Rozvadivska, Mykolaivska
		Yavorivskyi	Novoiavorivska, Mostyska, Yavorivska, Ivano-Frankivska, Shehynivska

Location map

Diagram of the hydrodynamic system on the Polish-Ukrainian border



1 – infiltration of unpolluted water,
2 – flow direction of unpolluted groundwater,
3 – seepage of polluted water,
4 – flow direction of polluted groundwater,
5-9 – types of pollution sources (A-Agriculture, F – Fertilizers, T – Transport, P – Municipal).

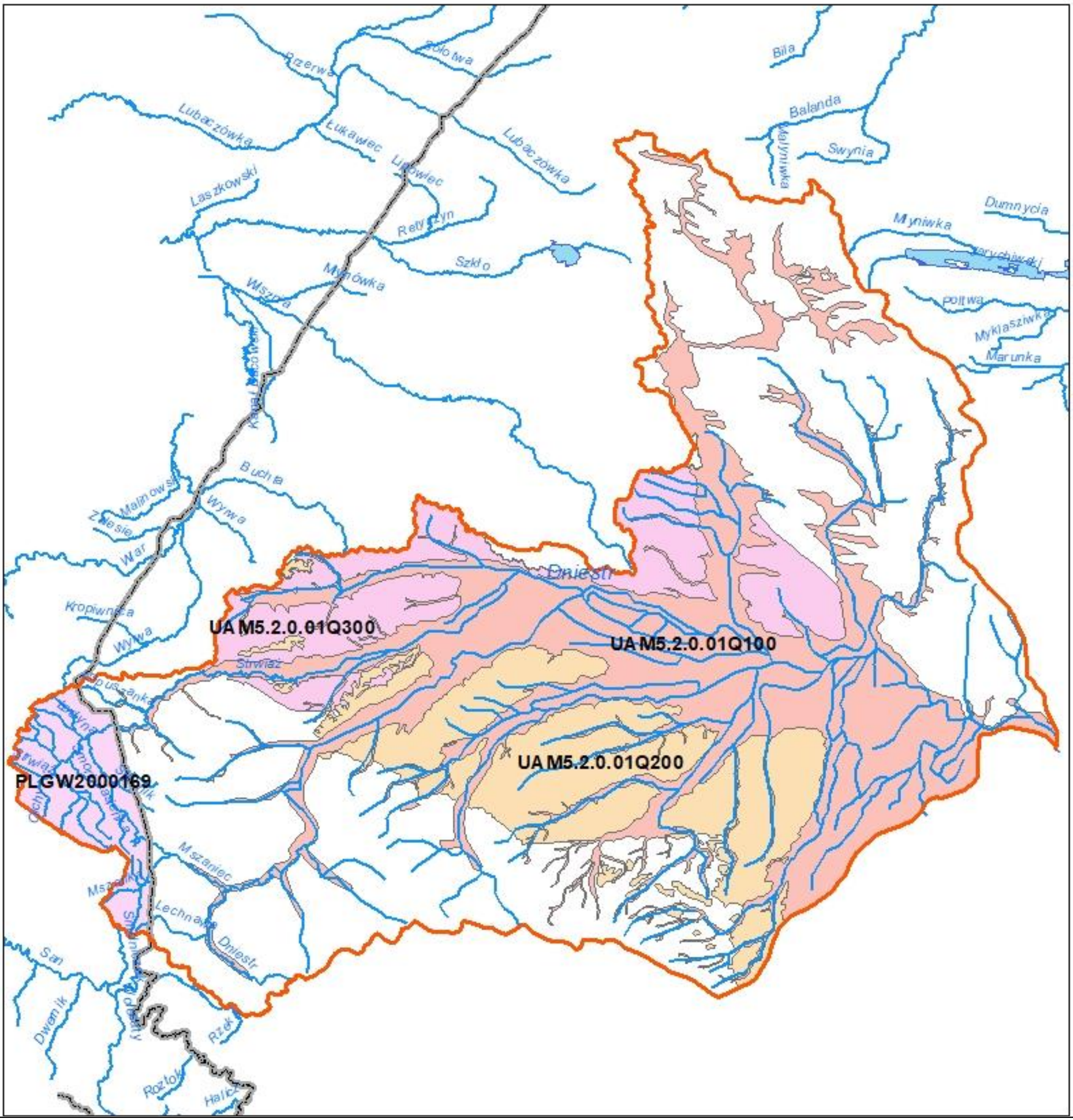
Physical-geographical region

Poland		Ukraine	
Province	Macroregion	Zone	Region
Eastern Carpathians with Eastern Subcarpathia	Wooded Carpathians	Western Ukraine	Roztocko-Opilski
		Ukrainian Carpathians	Carpathian Highlands, Outer Carpathians

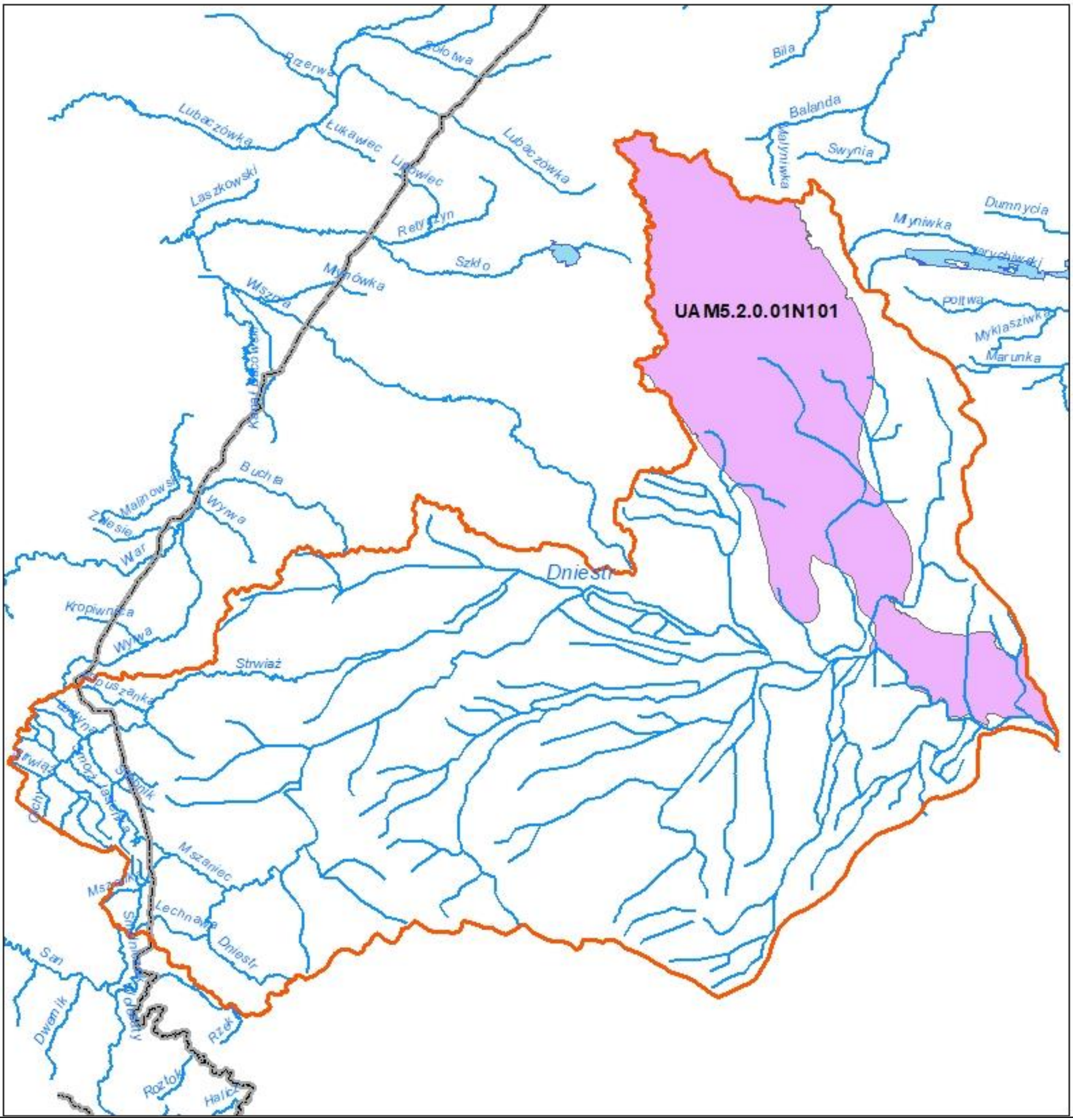
Main Rivers

Poland	Ukraine
Strwiąż, Mszaniec, Stebnik, Jasieńka	Dniester, Bolozivka, Stryvihor, Vereshchytsia, Cherkhavka, Tysmenytsia, Kolodnytsia, Zubra, Shchyrka, Struha, Trudnytsia, Brontsi, Stupnianka Mala, Ripchanka, Stupnytsia, Letnianka, Liutychynka

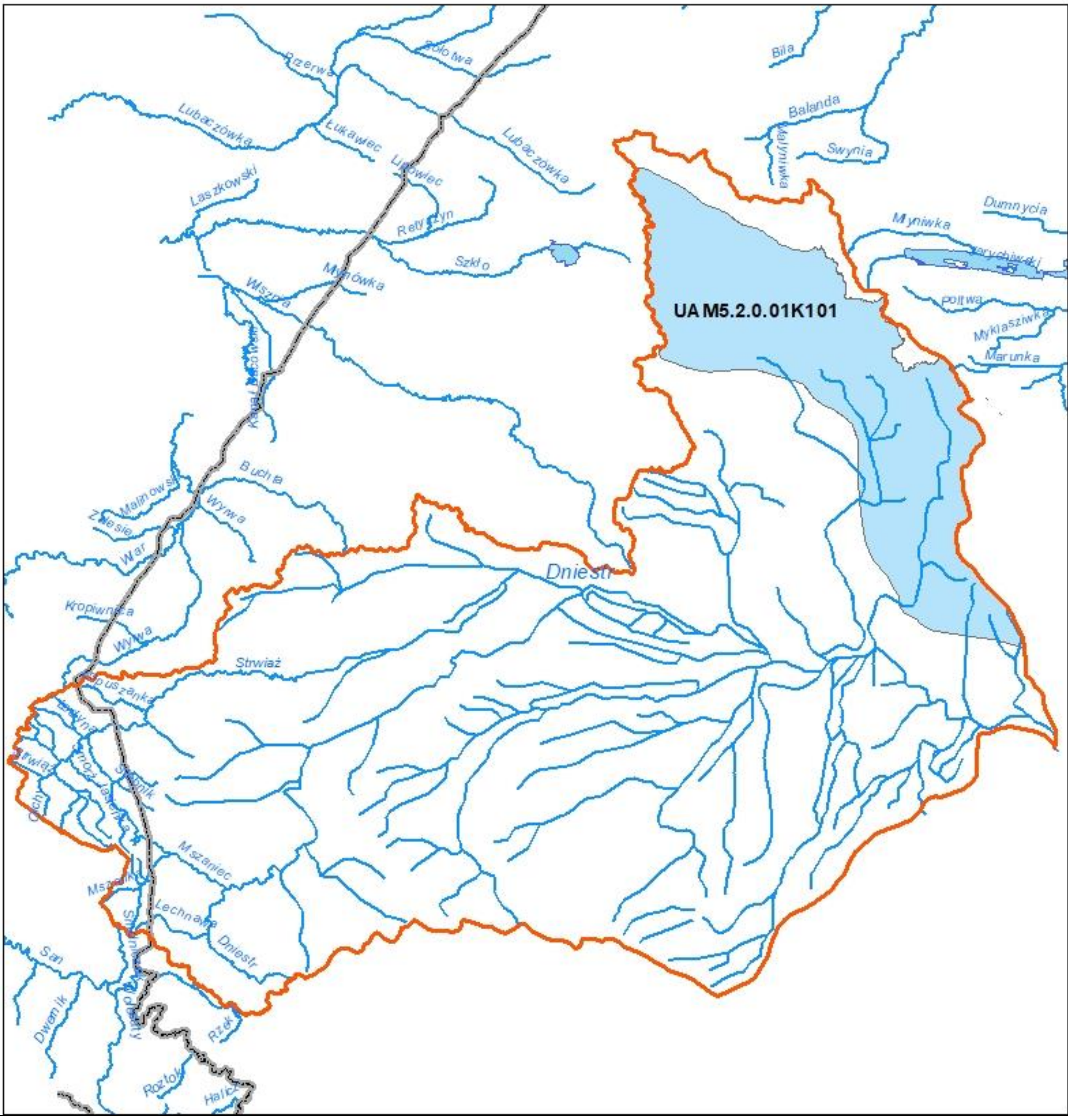
Groundwater Bodies	
Poland	Ukraine
Quaternary GWB	
No: PLGW2000169	No: UAM5.2.0.01Q100, UAM5.2.0.01Q200, UAM5.2.0.01Q300



Miocene GWB	
	No: UAM5.2.0.01N101



Upper Cretaceous GWB	
	No: UAM5.2.0.01K101,



Land use

Poland		Ukraine	
% of anthropogenic areas	3,73	% of anthropogenic areas	11,05
% of agricultural areas	33,71	% of agricultural areas	54,8
% of forest and green areas	62,55	% of forest and green areas	32,63
% of wetlands	0	% of wetlands	0,57
% of water areas	0,01	% of water areas	0,95

<table>
<tr><th colspan="4">Characteristics of transboundary aquifer</th></tr>
<tr><th colspan="2">Poland</th><th colspan="2">Ukraine</th></tr>
<tr><td rowspan="2">Q aquifer (Holocene, Pleistocene)</td><td rowspan="3">Lithology – sands, gravels, peables;
Type of aquifer – porous;
Groundwater table type – unconfined;
Depth to the aquifer – 2-10 m;
Thickness of the aquifer – 2-5m</td><td>Q aquifer - UAM5.2.0.01Q100 (Holocene, Pleistocene)</td><td>Lithology – sands, sandy loam, loam, gravel, pebbles;
Type of aquifer – porous;
Groundwater table type - unconfined;
Depth to the aquifer – 0,3-9,3 m;
Thickness of the aquifer – 1,5-20 m</td></tr>
<tr><td>Q2 aquifer - UAM5.2.0.01Q200 (Pleistocene)</td><td>Lithology – loams, clays, sands, pebbles;
Type of aquifer – porous;
Groundwater table type - unconfined;
Depth to the aquifer – 1-23 m;
Thickness of the aquifer – 1-28 m</td></tr>
<tr><td></td><td>Q2 aquifer - UAM5.2.0.01Q300 (Pleistocene)</td><td>Lithology – loams, sandy loams, sands;
Type of aquifer – porous;
Groundwater table type - unconfined;
Depth to the aquifer – 0-15 m;
Thickness of the aquifer – 5-25 m</td></tr>
<tr><td></td><td></td><td>N1 ($N_1b_2+N_1b_3$) aquifer - UAM5.2.0.01N101 (Miocene)</td><td>Lithology – limestone, sandstone, sands, gypsum, anhydrite;
Type of aquifer – porous-fractured;
Character of the aquifer - confined;
Depth of the aquifer – 0,5-70 m;
Thickness of the aquifer – 30-120 m</td></tr>
<tr><td></td><td></td><td>Cr3 aquifer - UAM5.2.0.01K101 (Upper Cretaceous)</td><td>Lithology – marl, chalk;
Type of the aquifer – fractured;
Groundwater table type - confined;
Depth to the aquifer – 10-80 m;
Thickness of the aquifer – 10-80 m</td></tr>
</table>

Pg-Cr (flysch) aquifer (Paleogene-Cretaceous)	Lithology – sandstones; Type of the aquifer –fractured; Groundwater table type - confined; Depth to the aquifer – 15-60 m; Thickness of the aquifer – 10-40 m	Pg-Cr (flysch) aquifer (Paleogene-Cretaceous) – local occurrence	Lithology – marl, chalk; Type of the aquifer – fractured; Groundwater table type aquifer - confined; Depth to the aquifer – 10-80 m; Thickness of the aquifer – 10-80 m

Scheme of water circulation

Groundwater recharge of the Quaternary and Flysch levels occurs as a result of precipitation infiltration and is possible throughout the area of their occurrence. In the case of the flysch layer, due to the varied relief and significant slopes of the terrain, surface runoff plays an important role. For the flysch zone, the areas of the most intensive groundwater recharge are the higher parts of the terrain, and the drainage zones are river valleys. Within the flysch zone, groundwater flow is possible only in the zone of active water exchange and takes place in accordance with the morphology of the area. Deeply cut streams, which are tributaries of the Wiar and Strwiąż rivers, drain the fractured massif and create local circulation systems. An important role in the circulation of groundwater is played by faults and dislocation zones, associated with them are zones of increased drainage of groundwater manifested in the occurrence of springs with significant discharge. Wiar and Strwiąż drain both, the Quaternary aquifer (own alluvium) and the Paleogene-Cretaceous aquifer (directly or through alluvium). Due to the morphology of the terrain and the shallow impermeable substrate (the permeable zone reaches a maximum depth of 80 m), it is not possible to develop other than local circulation systems.

Hydrochemical types of groundwater

HCO_3-Ca, HCO_3-SO_4-Ca, HCO_3-Ca-K, HCO_3-Ca-Mg

Exploitation resources Q (m^3/h)

Poland		Ukraine	
Q	0	Q	2999,6
Pg-Ng	31,5	Ng	3177,3
Cr	0	Cr	1264,1
Q-Pg-Ng	0	Q-Pg-Ng	1975,8
Pg-Ng-Cr	0	Pg-Ng-Cr	394,8

Quantitative resource pressures

Poland	Ukraine
None	Depression cones related to the abstraction of groundwater in the municipal and medical sectors (spa intakes exploiting the Miocene level)

Pollution pressures from diffuse sources

Poland	Ukraine
None	Occurrence of areas susceptible to nitrate pollution from agriculture. Significant share of urbanized areas with unregulated water and sewage management. The influence of the Lviv agglomeration and other large cities - Sambir, Novy Rozdil.

Pollution pressures from point sources			
Poland		Ukraine	
Wastewater treatment plant	1	Wastewater treatment plant	38
Waste landfills	2	Waste landfills	12
Natural vulnerability to groundwater pollution			
Poland		Ukraine	
% very high	74,84	% very high	24,4
% high	0	% high	0,45
% average	0	% average	0
% low	0	% low	15,82
% very low	0	% very low	9,62
% no rating	25,16	% no rating	49,71
Groundwater risk from diffuse and point pollution sources			
Poland		Ukraine	
% very high	0	% very high	0,16
% high	0,44	% high	0,42
% average	0	% average	0,07
% low	33,99	% low	32,24
% very low	39,37	% very low	17,18
% no rating	26,2	% no rating	49,93

3. Identifying of significant pressures

3.1. Pollution pressures from diffuse sources

The analysis of pressure on the chemical status of groundwater in relation to diffuse source was carried out on the basis of three types of characteristic indicators:

- indicator for agricultural pressures (as the share of agricultural areas in the area of calculation units);
- indicator for municipal pressures (the number of people not connected to the sewage system in administrative units and the load of organic compounds);
- indicator for pressures related to industry and urbanization (as the share of areas with urbanization and industrial development in the area of computing units).

The research area covers the areas on both sides of the Polish-Ukrainian border along its entire section from the Carpathians in the south to Polesia in the north. The border between Poland and Ukraine is 537 km long and runs through the Eastern Beskids, Northern Podkarpacie, the Lublin-Lviv Upland, the Volhynian - Podolian Upland and the Volhynian Polesie. In the hydrographic system, the study area covers the border fragments of the Bug, San and Dniester catchments (Figure 1).

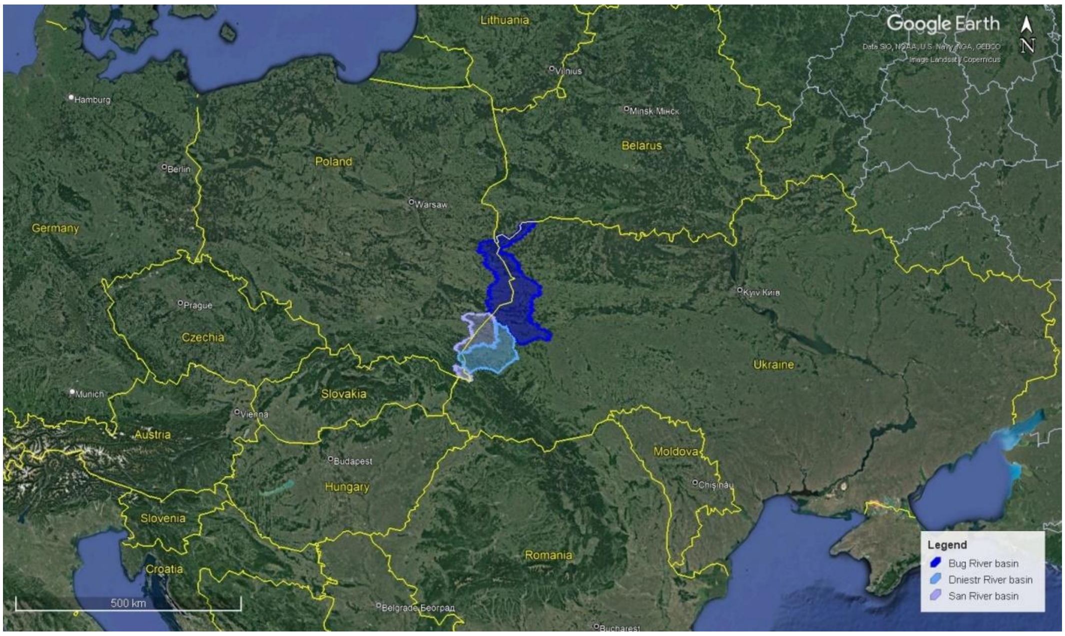


Figure 1. Overview map of the location of the basins of the Bug, San and Dniester Rivers

The boundaries were drawn along surface watercourses and morphological watersheds. In the north-east, the boundary of the research area runs along the watershed line separating the Dnieper basin from the Vistula basin in Ukraine. Next, the border was drawn along the watershed line separating the Vistula basin from the Dniester basin in Ukraine. Further south, the border is marked by a watershed line between the catchments of the left tributaries of the Dniester - Zubra and Svirż, and later the right tributaries of the Dniester - Stryj and Tysmenytsia. In the south, the boundary line was drawn along the watershed line closing the catchment area of the San River. In Poland, from the south, the border runs along the watershed line separating the Dniester basin from the Vistula basin. Further north, the border is marked by the channels of the San, Lubaczówka, Sołotów and Świdnica. From the north-west, the border of the area is marked by the surface divisions closing the catchments of the left tributaries of the Bug - Rata, Sołokija, Warężanka, Huczwa, Wełnianka, Udal, Ucherka and Włodawka. The total area of the study area is 26,073 km^2, of which:

- 15 575 km^2 is located in the Bug catchment;
- 4 569 km^2 – is located in the San catchment;
- 5 929 km^2 – it is located in the Dniester catchment.

For the purposes of calculating the anthropopressure indicators, this area was divided into calculation blocks using a constant discretization step of 1000 m. As a result, a discretization grid consisting of 27,024 calculation blocks was created (Figure 2).

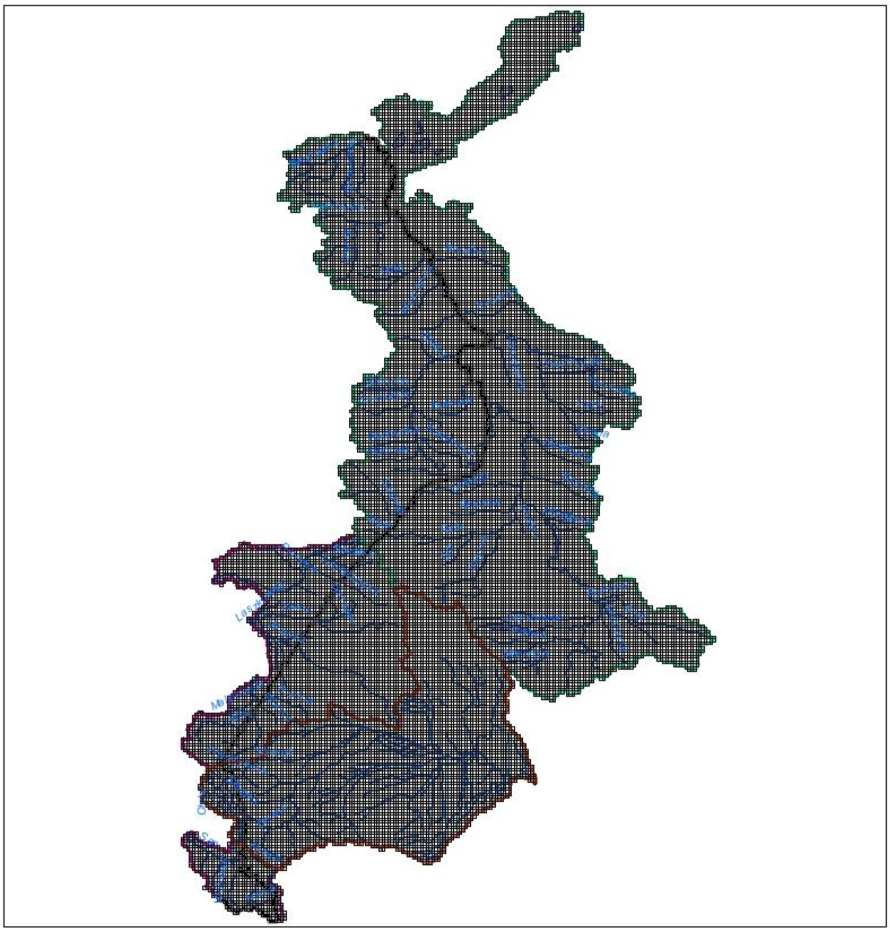


Figure 2. Computational grid within the study area within the catchment area of the Bug, San and Dniester rivers

In the analysis of agricultural pressure for Poland, publicly available Corine Land Cover 2018 data was used. However, the lack of an appropriate database for Ukraine made it necessary to create its own version using an analogous method based on the interpretation of Sentinel-2 satellite data. The result was a common land use database (Figure 3, Figure 4, Figure 5).

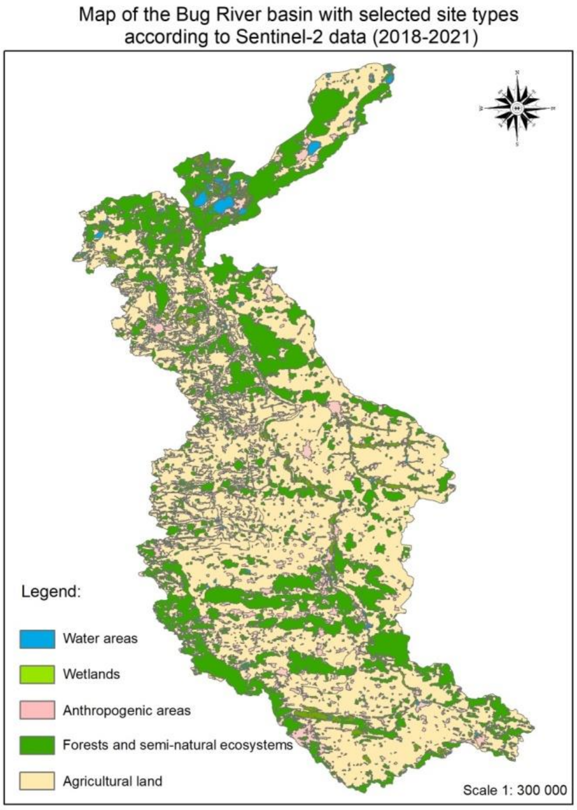


Figure 3. Land use in the Bug catchment area

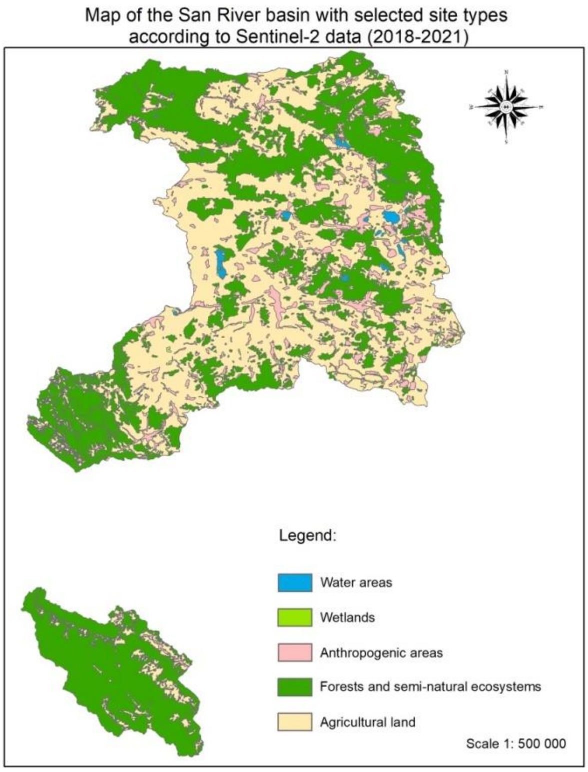


Figure 4. Land use in the San catchment area

Map of the Dniester River basin with selected site types according to Sentinel-2 data (2018-2021)

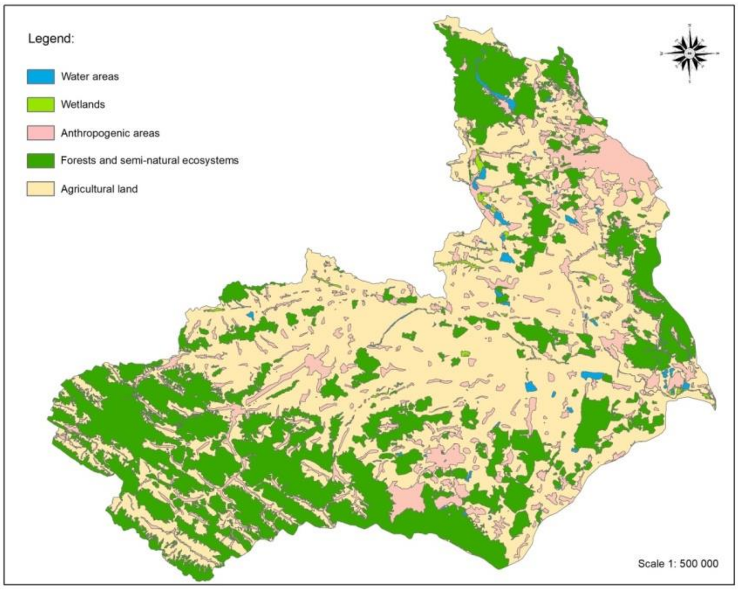


Figure 5. Land use in the Bug catchment area

On the basis of the above land use map, agricultural pressure was calculated as the share of agricultural areas (from 0 to 1) in the area of individual grids of the discretization grid. The resulting map is shown in Figure 6.

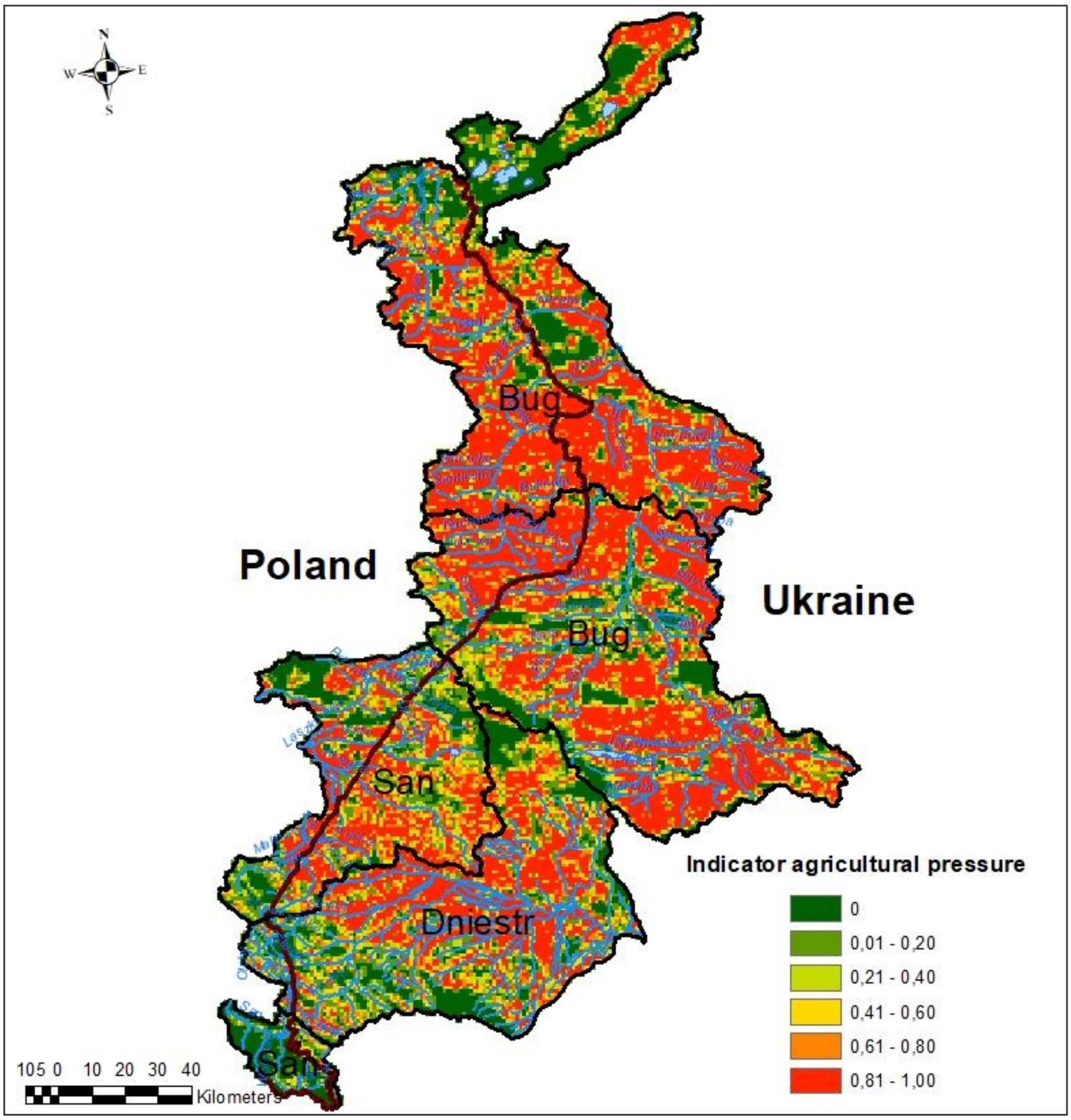


Figure 6. Intensity of agricultural pressure of a diffuse character

The southern fragment of the Bug catchment is the most exposed to agricultural pressure. In this area, the share of agricultural land with a high pressure index (over 0.8) is 42.2%. The northern fragment of the Bug catchment and the Dniester catchment are also characterized by a high agricultural pressure index (the pressure index over 0.8 is observed in approx. 33-34% of the area). The high degree of agricultural development of these catchments results from natural conditions - greater flatness of the area and a developed network of rural settlements. In the mountain region, a distinct zone of dominance of natural, forested areas is developed. Values of the agricultural pressure index broken down into individual catchments are presented in Table 2

Table 3. Agricultural pressure indicator in research catchments

Agricultural pressure indicator	The northern part of the Bug catchment area	The southern part of the Bug catchment area	The northern part of the San river basin	The southern part of the San river basin	Dniester catchment
0 (brak)	38,4%	36,8%	48,9%	86,4%	46%
0,01-0,20	4,5%	2,1%	1,6%	1,9%	1,3%
0,20-0,40	6,9%	3,6%	3,9%	3,4%	3,3%
0,40-0,60	7,1%	5,5%	6,4%	4,1%	5,7%
0,60-0,80	10,4%	9,8%	11,1%	2,8%	9,8%
0,80-1,00	**32,7%**	**42,2%**	28,1%	1,4%	**33,9%**

Another factor of diffuse pressure is the flow of pollutants from urban and industrial areas. Due to the lack of measurement data, an indicator that reflects the spatial distribution of this pressure to a large extent was used - the share of areas with industrial and urban development in the area of computing units. The resulting map is shown in Figure 7, and the values of the indicator broken down into individual catchments – in Table3.

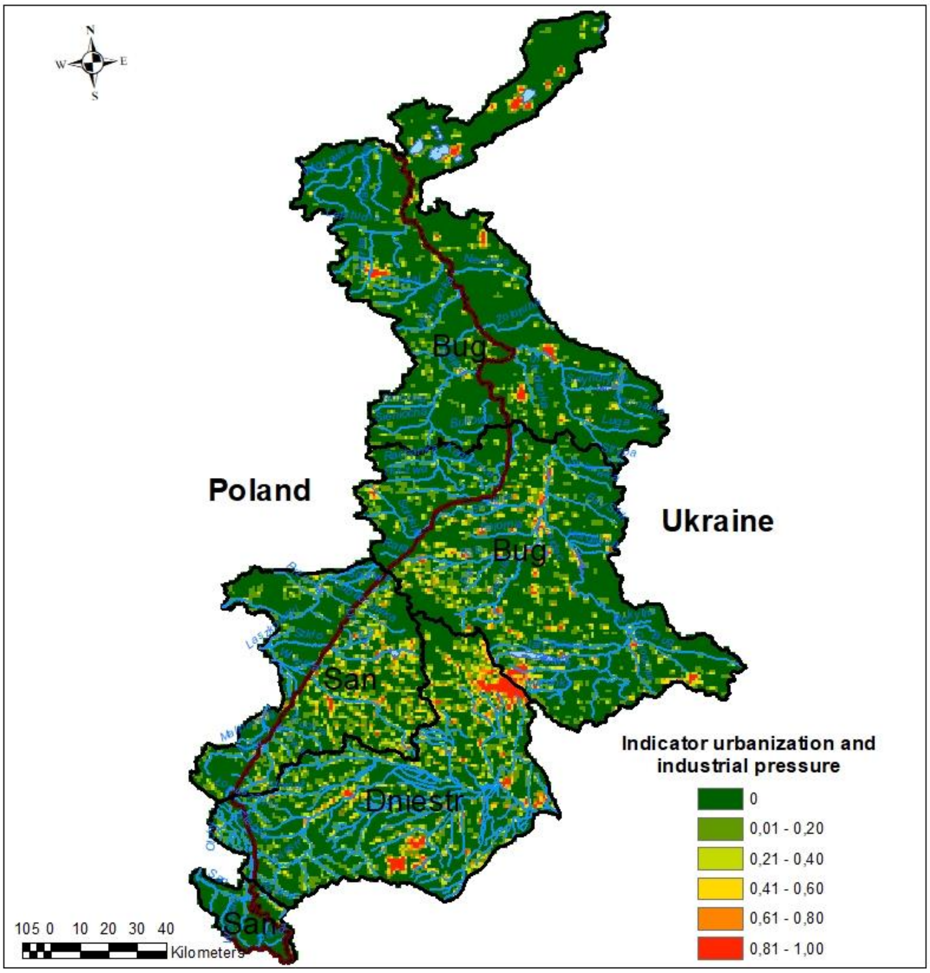


Figure 7. Intensity of urban and industrial pressure of diffuse character

Table4. Indicator of urbanization and industrial pressure in research catchments

Indicator of urbanization and industrial pressure	The northern part of the Bug catchment area	The southern part of the Bug catchment area	The northern part of the San river basin	The southern part of the San river basin	Dniester catchment
0	96,7%	93,9%	92,5%	98,5%	89,3%
0,01-0,20	0,9%	1,4%	1,9%	0,7%	1,9%
0,20-0,40	0,8%	1,5%	2,3%	0,6%	2,4%
0,40-0,60	0,4%	1,2%	1,5%	0,2%	2%
0,60-0,80	0,3%	1%	1,2%	0%	1,7%
0,80-1,00	0,9%	1%	0,6%	0%	2,7%

Generally, in the study area, the indicator of urban and industrial pressure estimated by the share of areas used in this way is negligible, because they do not occur in over 90% of the area. Regardless of the insignificant share of the area used for industrial purposes, the impact on the chemistry of groundwater can be significant. Water runoff from urbanized areas is associated with the greatest threats to the quality of ground- and surface waters. Therefore, at the stage of estimating the total pressure using the weight-rank method, this indicator was given the highest rank, determining the high risk to groundwater.

An important factor of groundwater pollution in the study area is disordered municipal management in relation to municipal sewage. In rural areas, especially in Ukraine, the degree of centralized sewage system is negligible, as well as the development of household sewage treatment plants. A widely used solution is the use of septic tanks, leaks of which often result in the filtration of sewage directly into the aquifer. The occurrence of such objects is so numerous that it was decided to relate this factor to the sources of diffuse pollution, not point sources. Municipal pressure is most often estimated on the basis of the percentage of the population not connected to the sewage system in administrative units (Figure 8).

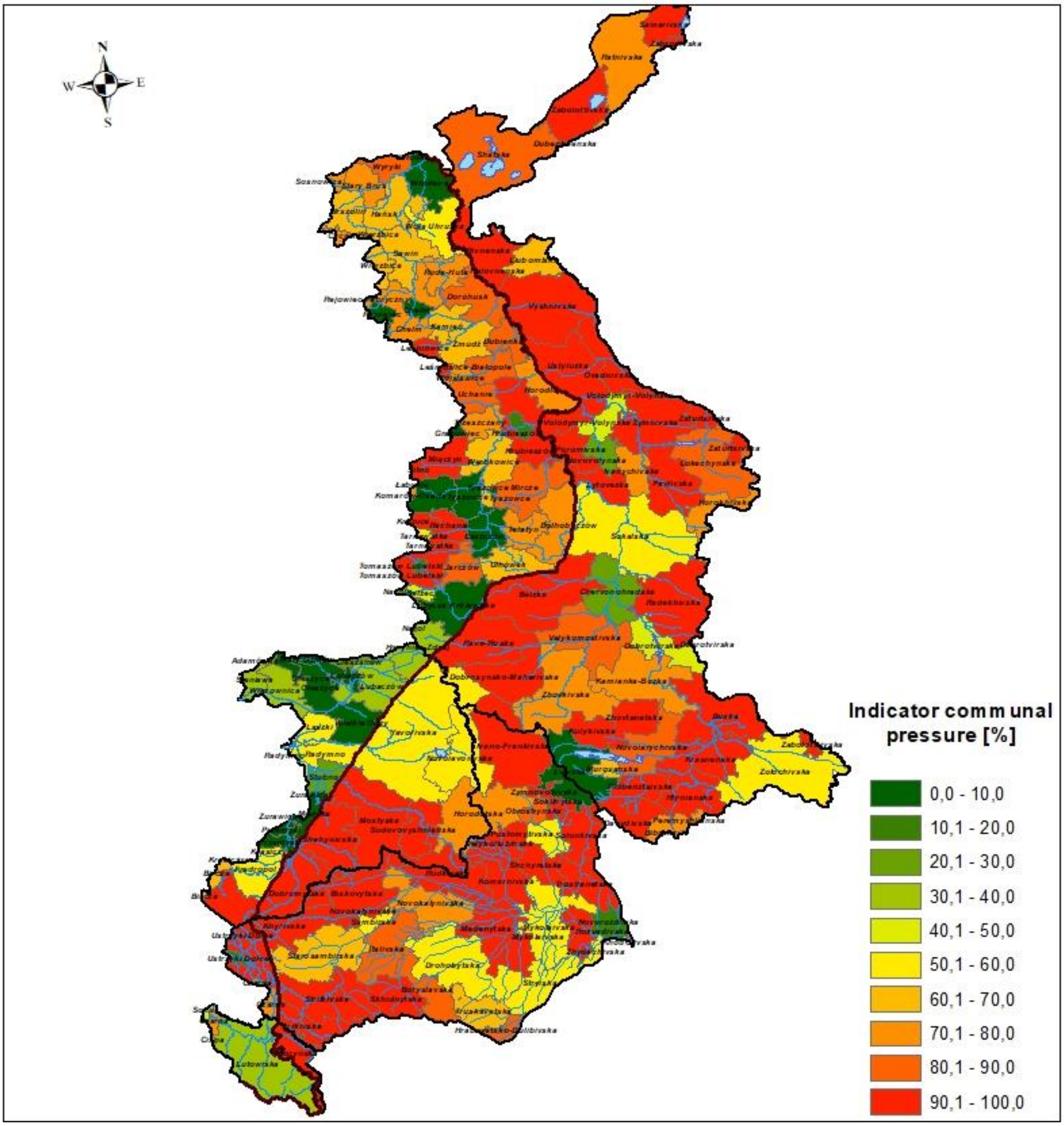


Figure 8. Percentage of population not connected to the sewage system within administrative units

The analysis of data on the connection of households to the sewage network showed significant differences on both sides of the border (Figure 8). On the Polish side, in half of the communes (45 out of 84), the percentage of the population not using the group sewage system exceeds 50%, and in eight communes this percentage is higher than 90%. On average, in communes on the Polish side, 52.4% of the total population uses the sewage system. On the Ukrainian side, the development of the sewage network is definitely lower. In the majority of communes (81 out of 89), the percentage of the population connected to the sewage system does not exceed 50%, and in 47 (half) communes over 90% of the population does not use the group sewage system. On average, in communes on the Ukrainian side, only 18.4% of the population uses the group sewage system. As indicated by the above data, the level of sewage system in the communes of the Polish-Ukrainian border area is quite low on both sides of the border. Therefore, communal pressure should be considered as the most threatening to the chemical status of groundwater.

A widely used indicator of municipal pressure in the River Basin Management Plans is the amount of population not connected to the group sewage system, converted into an indicator of the load of organic pollutants expressed in terms of BOD_5 and COD. The equivalent charge of BOD_5 produced by one inhabitant is assumed at the level of 60 g/day/person, COD - 110 g/day/person. The communal pressure is then calculated as the annual load of organic pollutants expressed as the product of the population not connected to the sewage system in administrative units and the unit BOD_5 and COD load of the wastewater produced. Figure 9 shows a map of the number of people not connected to a group sewage system per km^2 of land area (population density) within the boundaries of administrative units.

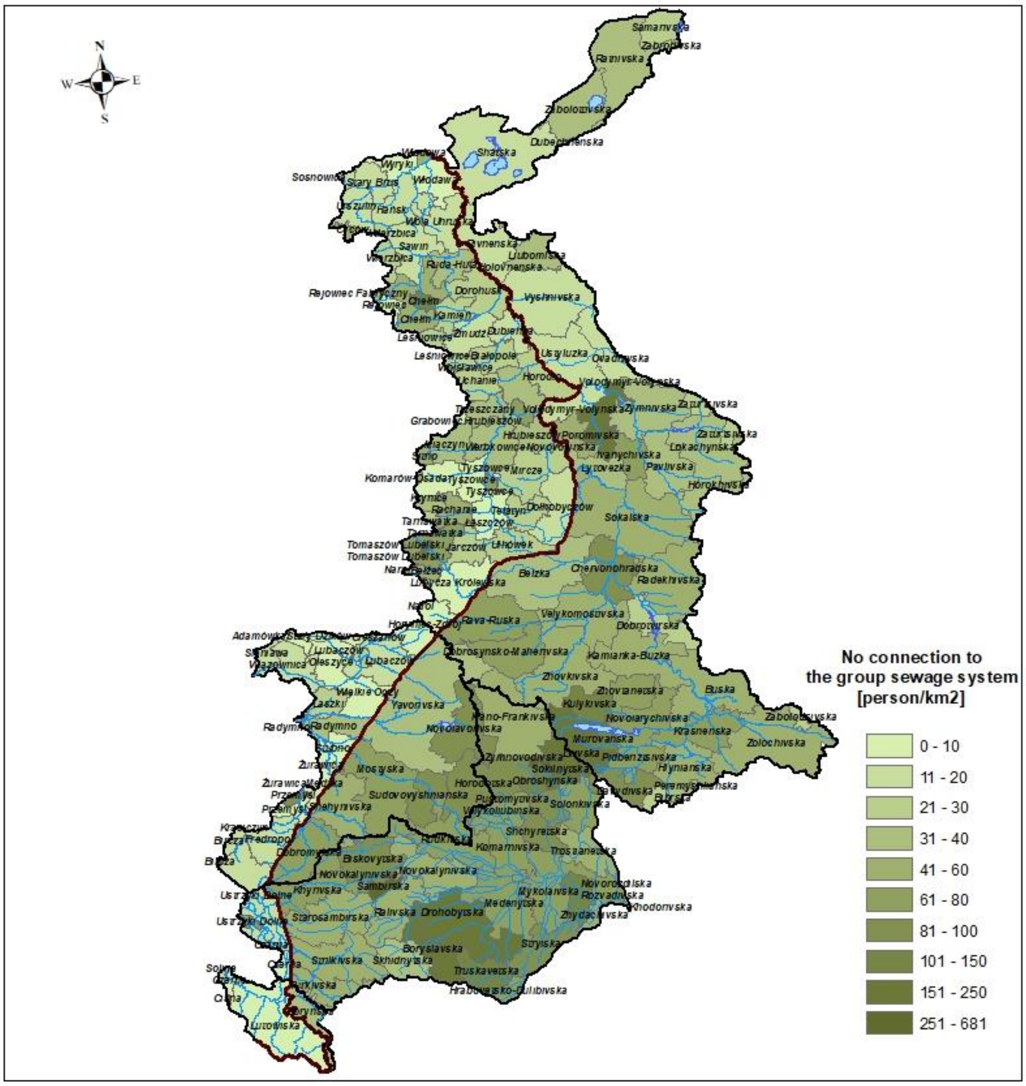


Figure 9. Population density not connected to the group sewage network in administrative units

This indicator, compared to the previous one (percentage of population not connected to the sewage system), characterizes the intensity of communal pressure better because it takes into account information on population density. In this way, the spatial distribution of communal pressure reflects a logical regularity - the pressure intensity is proportional to the density of the population not connected to the sewage system. As shown in Figure 9, the maximum values of over 250 people/km^2 on both sides of the border are observed in highly urbanized administrative units - Lviv, Truskavetsk, Volodymyr-Volynski, Drohobych, Sambir (Ukraine) and Chełm, Tomaszów Lubelski, Przemyśl (Poland).). On the other hand, the sparsely populated Carpathian area (the communes of Lutowiska, Ustrzyki Dolne) shows the lowest values - about 1 person/km^2. On the Ukrainian side, the development of the sewage network is definitely lower. On average, 78 people/km^2 do not use the group sewage network in territorial communities. On the Polish side, this indicator is three times lower – it reaches 27 people/km^2.

Against this background, the data on the daily load of organic pollutants as a result of municipal pressure, broken down by catchments, looks interesting (Table4).

Table 5. Load of organic pollutants generated by households not connected to the group sewage system in the study area

Catchment	**Load of organic pollutants, tonnes/day/km2**							
	Poland				Ukraine			
	BOD_5		COD		BOD_5		COD	
	tonnes/24h	kg/24h/km^2	tonnes/24h	kg/24h/km^2	tonnes/24h	kg/24h/km^2	tonnes/24h	kg/24h/km^2
Bug	7,52	0,48	13,79	0,89	30,22	1,94	55,40	3,56
San	1,48	0,32	2,72	0,60	8,77	1,92	16,09	3,52
Dniester	0,28	0,05	0,51	0,09	29,93	5,05	54,88	9,26

The analysis of data on the load of organic pollutants as a result of municipal pressure per 1 km^2 of the area of individual catchments showed significant differences on both sides of the border. On the Polish side, in the catchment area of the Bug and San, the load of organic pollutants expressed by BOD_5 is about 0.4-0.5 kg/24h/km^2 and 0.05 kg/24h/km^2 - in the catchment of the Dniester River. On the Ukrainian side, due to the low development of the sewage network and high population density, this load is over 4 times higher in the Bug catchment area (1.94 kgBOD_5/24h/km^2), 6 times higher in the San catchment area (1.92 kgBOD_5/ 24h/km^2) and 101 times higher in the Dniester catchment (5.05 kgBOD_5/24h/km^2). Currently, the situation is even worse because the population density data on both sides of the border do not contain information on the number of refugees as a result of the war in Ukraine, and it is known that the border areas received the largest number of them.

3.2. Pollution pressures from point sources

The analysis of point pressures was carried out with particular emphasis on pressures whose impact on groundwater may be noticeable in water chemistry. First of all, the focus was on landfills and the discharge of municipal and industrial sewage into waters or land, which are subject to the National Pollutant Release and Transfer Registers.

In the case of wastewater discharge pressure, information was used on the type of wastewater (municipal or industrial), the way it is treated, the maximum capacity of the treatment plant and the wastewater receiver. For this purpose, available official information on both sides of the border was used. The spatial distribution of sites and the maximum possible amount of sewage discharges is clearly uneven (Figure 10). This is mainly due to the density of the settlement network and the degree of urbanization. On the Polish side of the research area, small towns and appropriately adjusted low efficiency of treatment plants dominate. In the Ukrainian part, apart from the large Lviv agglomeration with a population of over 721,000 people, there are numerous cities with a population of over 20,000 people - Chervonograd, Novovolynsk, Volodymyr-Volynskyi, Novoiavorivsk, Zolochiv, Sokal, Drohobych, Novyi Rozdil. Therefore, on the Ukrainian side, a larger share of treatment plants with higher efficiency is observed. Based solely on official data, there are 117 wastewater treatment plants in the study area (20 of them - industrial facilities, the rest - municipal), almost all of which have a river or canal as a sewage receiver. The load of sewage discharges on the main rivers of the study area is characterized by Table 6.

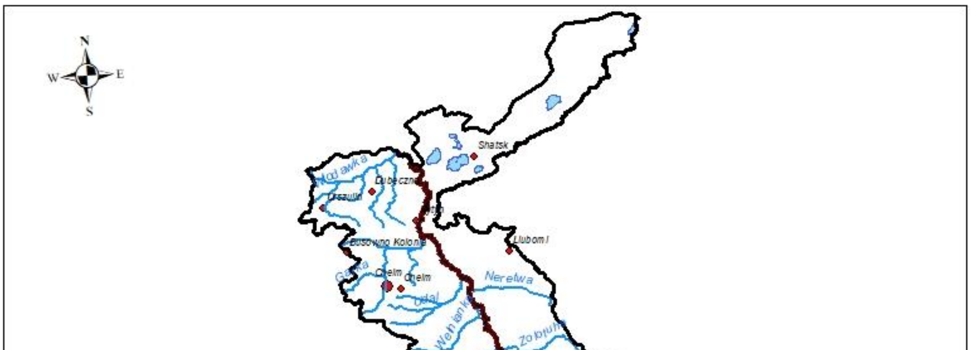


Figure 10. Municipal and industrial wastewater discharge sites and maximum capacity of treatment plants

Table 6. Load of sewage to the main rivers

River	Number of municipal and industrial sewage discharge sites	
	Poland	Ukraine
	The Bug catchment	
Bug	2	13
Włodawka	1	0
Uherka	1	0
Huczwa	4	0
Sołokja	2	1
Luha	0	3
Rata	0	1
Yarychivka	0	4
Poltva	0	2
Zolochivka	0	1
Marunka	0	1
Tymkovetsky stream	0	1
Semen stream	0	1
Kamianka	0	2
Kholoivka	0	1
Kyisky stream	0	1
Svynia	0	1
Balanda (Mlynivka)	0	1
Hapa	0	1
Luha-Svynoryika	0	1
	The San catchment	
San	3	0
Lubaczówka	4	0
Shklo	1	8
Vyshnia	0	7
Wiar	1	0
Zavadivka	0	1
Rakiv	0	1
Zeleny Stream	0	1
Butsivsky Channel	0	1
Pyla	0	1
Hnoienets	0	1
	The Dniester catchment	
Dniester	0	8
Strwiąż	1	2
Shchyrka	0	3
Tysmenytsia	0	3
Vereshchycia	0	8
Zubra	0	4

Considering the discharge of wastewater as a factor of significant pressure is related to the fact that the inadequate level of their treatment, or even the lack of it, is a common problem in Ukraine.

Table 6 shows the chemical components of wastewater with the highest load.

Table 6. Annual load of the main components of pollutants discharged into rivers in Ukraine with sewage as of 2021

River	BOD_5, tonnes /year	COD, tonnes /year	N-NH_4, tonnes /year	NO_3, tonnes /year	PO_4, tonnes /year	Petroleum , kg/year	Surface Active Agents, kg/year
The Bug catchment							
Bug	117.7	620.6	24.1	97.7	19.8	87.7	643.7
Zolochivka	12.6	31.7	1.0	5.0	2.4	-	58.1
Poltva	1541.7	6688.8	185.1	986.0	138.9	-	17051.1
Yarychivka	21.0	54.0	5.7	1.0	2.0	7.4	221.9
Marunka	0	0.2	-	-	-	-	0.6
Tymkovetsky stream	0.1	0.4	0	0.1	0	-	0.8
Semen stream	0	0.1	-	-	-	0.1	0.9
Kamianka	6.7	19.4	1.0	1.3	0.6	30.6	131.3
Kholoivka	0.7	1.5	0	0.5	0	-	5.3
Kyisky stream	0.6	2.3	0.1	0.4	0.1	3	2.4
Rata	5.2	20.1	0.8	2.5	0.6	3.9	28.7
Svynia	4.0	15.6	0.2	3.5	0.4	-	10.7
Balanda (Mlynivka)	0.2	0.2	0	0	0	3.2	0.2
Solokia	0	0.1	-	-	-	-	-
Luha	6.7	47.7	4.7	7.9	2.5	-	-
Hapa	8.5	0.6	0.1	0.1	0	-	-
Luha-Svynoryika	0.4	2.4	0.2	0.4	0.1	-	-
The San catchment							
Zavadivka	0.3	1.3	0.2	0.3	0.2	-	11.2
Vyshnia	2.5	4.4	0.2	2.2	0.2	-	10.0
Rakiv	3.0	6.9	0.1	0.9	0.1	-	5.0
Zeleny Stream	0.1	0.4	0	0.6	0	-	1.2
Butsivsky Channel	0.3	0.7	0	0.3	0.1	-	0.5
Shklo	1.2	4.7	0.3	0.7	0.4	1.7	15.4
Pyla	1.6	4.3	0.1	0.2	0	-	10.3
Hnoienets	13.8	32.2	1.5	3	0.2	-	21.6

The analysis of the above data showed that in 2021, 7.6 thousand tonnes of organic compounds (according to COD) were discharged with sewage into the Bug and San rivers in Ukraine, directly or through tributaries. Almost 88% of them - went through the Poltva River - a receiver of sewage produced by the Lviv agglomeration. Organic and biogenic compounds are the main factor in the development of eutrophication of surface waters. Nitrates and phosphates – have the largest share in the load of biogenic compounds to the rivers of the Ukrainian part of the study area. In 2021, 1.1 thousand tonnes of nitrates and 0.2 thousand tonnes of phosphates were discharged into the Bug River, and 8.2 and 1.2 tonnes into the San River, respectively. The effectiveness of wastewater treatment from phosphorus compounds in Ukraine is very low and does not exceed 20% due to the lack of technological modernization. Almost 97-99% of biogenic compounds end up in municipal sewage. The largest amounts of them are produced and dumped into the Poltva River by the “Lvivvodokanal” – a municipal company serving the Lviv agglomeration. According to 2021 data, 82% of N-NH_4, 88% of NO_3, 88% of NO_2 and 82% of PO_4 discharges hit the Poltva River. Large emissions of pollutants also take place at wastewater treatment plants in the towns of Chervonograd, Sokal, Radehiv, Rava-Ruska, Kamianka Buzka, Zhovkva (the Bug catchment area) and Yavoriv, Novoiavorivsk, Mostyska, Rudky (the San catchment area). For these facilities, emergency discharges of sewage without treatment are often used.

Landfills are the main point source of groundwater contamination in the study area. This problem is particularly threatening in Ukraine due to the dominance of non-modernized, obsolete facilities, where, due to leaky insulation, the migration of pollutants is facilitated. The obtained official information on landfills on both sides of the border contained the following data: landfill area, waste storage method, technical security, origin of the stored waste, type of waste deposited-hazard, condition of the landfill. The location and differentiation of landfills according to the area of the facility are shown in Figure 11. Their extended characteristics are given in Table 7, Table 8 and Table 9.

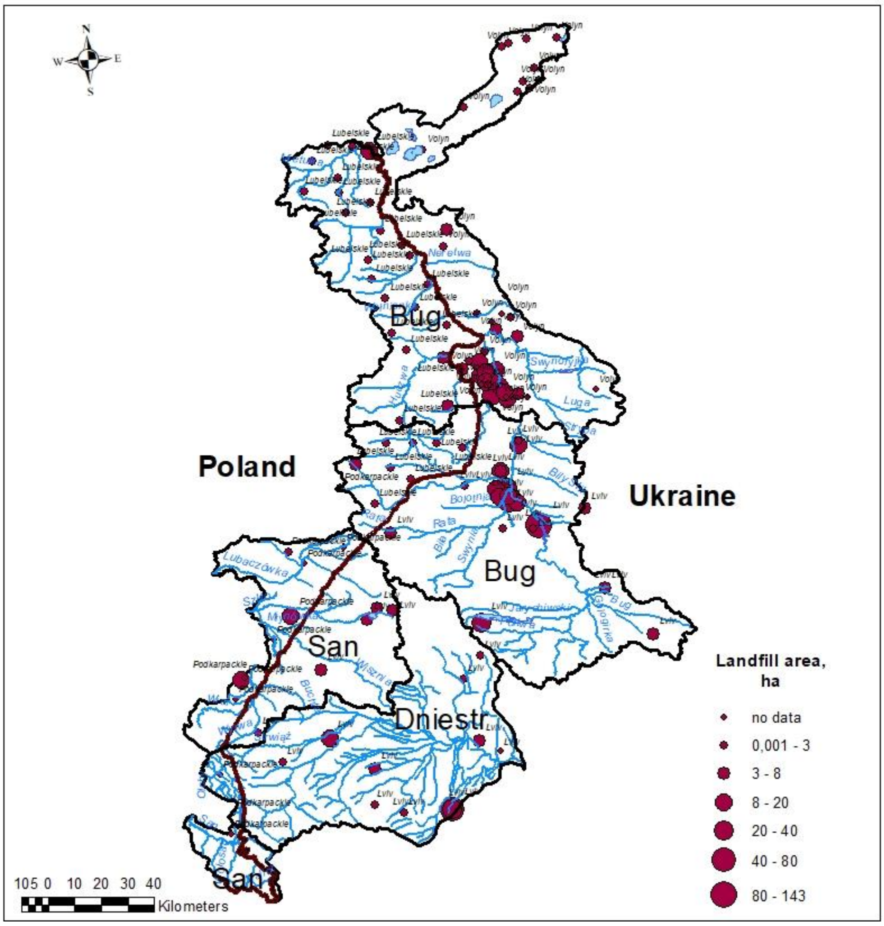


Figure 11. Location and size of landfills

Table 7. The number of landfills in the catchment area of the Bug by category

The condition of the landfill	Poland		Ukraine		
	Hazardous	Non-hazardous	Hazardous	Non-hazardous	No data
Open	1	3	26	25	1
Open but unused	0	7	1	0	0
Closed without reclamation	0	0	1	0	0
Closed during reclamation	0	1	1	1	0
Closed reclaimed	1	20	2	0	0
Closed during liquidation	0	0	7	0	0

Table 8. The number of landfills in the San catchment, broken down into categories

The condition of the landfill	Poland		Ukraine	
	Hazardous	Non-hazardous	Hazardous	Non-hazardous
Open	0	3	3	0
Open but unused	0	0	0	0
Closed without reclamation	0	0	2	0
Closed during reclamation	0	0	0	0
Closed reclaimed	1	6	0	0
Closed during liquidation	0	0	0	0

Table 9. The number of landfills in the Dniester catchment, broken down into categories

The condition of the landfill	Poland		Ukraine	
	Hazardous	Non-hazardous	Hazardous	Non-hazardous
Open	0	0	12	0
Open but unused	0	0	0	0
Closed without reclamation	0	0	0	0
Closed during reclamation	0	0	0	0
Closed reclaimed	0	2	0	0
Closed during liquidation	0	0	0	0

The analysis of data on the state of landfills showed significant differences on both sides of the border (Table 7, Table and Table). On the Polish side, 3 out of 45 landfills (2 - in the Bug catchment area and 1 - in the San River) pose a threat to groundwater, the rest are non-hazardous. Only 13 (10 - in the catchment of the Bug and 3 in the catchment of the San) out of 45 objects on the Polish side are currently functioning, the rest are recultivated or under reclamation. On the Ukrainian side, the safety of landfills is much lower. Most landfills (55 out of 82) pose a threat to groundwater, and in the catchments of the San and Dniester rivers - all of them. Most of the landfills (68 out of 82) are currently in operation, and 42 of them have the hazardous status. Among the 14 closed landfills (12 - in the Bug catchment, 2 - in the San catchment), 3 sites were left without reclamation. According to the water resources management plan for the Vistula catchment in Ukraine, over 130 landfills in the Bug catchment operate illegally without appropriate administrative permits. Most legal landfills do not meet environmental requirements and are a source of water pollution. The greatest danger is the communal and industrial landfill of the Lviv agglomeration, located near Lviv in Grybovychi. The volume of stored waste on the area of 33.3 ha is 13 million tons, including 200,000 tonnes – is a highly dangerous substance. The conditions of waste storage at this landfill do not meet any ecological standards. In 2016, water from the landfill drainage system flowed into the nearest Malehivka River - a tributary of the Poltva (the Bug catchment area), causing an ecological disaster. Landfills in Kamianka Buzka, Dobrotvir, Novy Yarychiv, Zapytiv, where the permissible capacity has been exceeded and there is a need for reclamation, pose a significant threat to the groundwater of the Bug catchment. In the San catchment area on the Ukrainian side, the total landfill area is 10.1 ha. The largest facilities are located in the villages of Novoiavorivsk, Borynia and Lypnyky.

Objects of the mining industry

Sulphur mining. There are two mining districts in the Precarpathian sulphur basin: Rozdil and Yavoriv. Rozdil district has Rozdil and Podorozhne deposits of native sulphur, and Yavoriv district has Yaziv and Nemyriv deposits (Figure 12). The deposits are located at depths ranging from 14 to 885 meters[11].

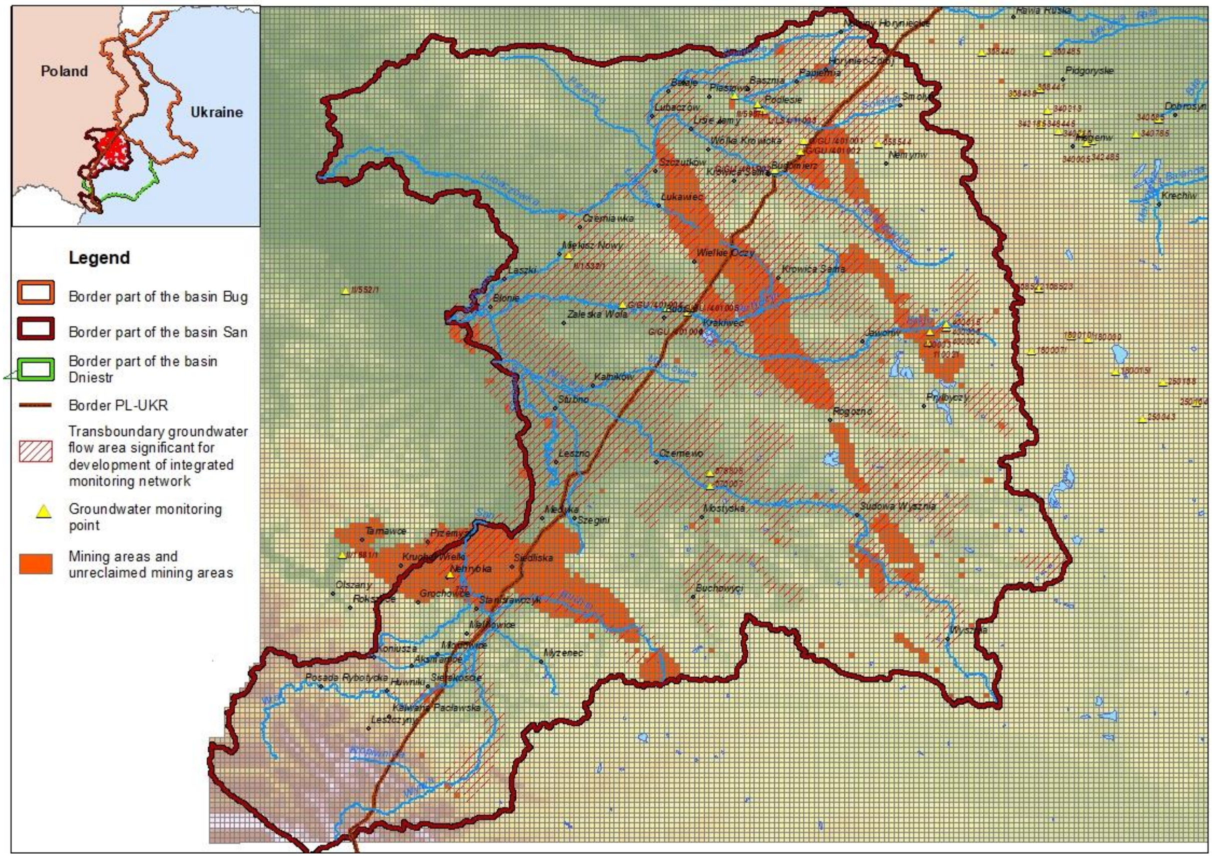


Figure 12. Location of sulphur mining areas and non-reclaimed sulphur mining areas within San river basin

Rozdil deposit is located in the floodplain and high above-floodplain terraces of the Dniester River, which flows 0.8-0.9 km from the southern border of the deposit.

The Podorozhne deposit is located in the Bilche-Volytsia zone of the Precarpathian Foredeep. The deposit is represented by a floodplain terrace of the Dniester River and its right tributary, the Svicha River, which flows in its southern part.

The Yaziv deposit is located in the area where the southwestern part of the East European Platform junctions with the Precarpathian Foredeep. Hydrologically, the Yaziv sulphur deposit is located in the basin of the San River with tributaries of the Shklo and Hnoienets Rivers.

[11] Panas, R.M., Malanchuk, M.S. 2011. Monitoring of geological and hydrological conditions and methods of development of sulfur deposits in the Precarpathian Basin (in Ukrainian with English summary). Geodesy, Cartography, and Aerial Photography, 74: 124–132

The Nemyriv sulphur deposit, extending from the west to the southeast, is located within the basin of the San River with an ore bed depth from 47 to 450 m.

Upper Cretaceous, Miocene, and Quaternary sediments are involved in the geological structure of the deposits. Mining of sulphur ores has been carried out since 1953 by open pit and underground smelting methods. The imperfect technology of sulphur extraction at the Yaziv, Podorozhne, and Rozdil deposits led to a change in the natural and historical geological environment and the formation of new factors for the dissolution of sulphate rocks, man-made activation of sulphate karst[12].

Since 2000, work has been carried out to maintain deposits in an ecologically safe state: drainage of former quarries, drainage. In 2003, by the decree of the Cabinet of Ministers of Ukraine, projects for the reclamation of lands disturbed by mining operations within the limits of the Yavoriv and Rozdil CEF "Sirka" were approved. Since 2007, native sulphur mining has been stopped due to unprofitability.

At the Yaziv sulphur ore deposit, natural sulphur was extracted mainly by the underground smelting method and partly by the quarrying method. The Nemyriv deposit was developed by underground smelting. The development of sulphur deposits was accompanied by the following landscape changes: the appearance of areas of land with destroyed plant and soil layers, pockets of post-technologically devastated land with a system of drainage ditches, fragmented vegetation and transformed and chemically polluted soils. After the sulphur extraction, the soils were contaminated with its residues and other harmful substances, which negatively affect groundwater quality. Sulphur content in the soil layer up to 20 cm is 2–3%, at a depth of 20–40 cm it decreases to 0.4–0.6%. The soil pH has also changed: it is 3–4, and in some areas, it is 1.5–2 (Savchuk). Without technical reclamation, such sites can be restored for decades[13].

In view of the above and the experience of reclamation of such objects in Poland, the largest element of the man-made landscape – the Yavoriv Sulphur Quarry – was flooded, and the resulting reservoir was recommended to be used for recreational purposes and, if necessary, for domestic and drinking water supply.

Its maximum depth reaches 75 m, in the areas of sulphur ore mining zones - 50–60 m, and within the internal dumps there are shallower areas with a depth of 10–30 m. The volume of the lake is 198 million m^3 with a water surface area of 694.2 ha. The lake is recharged by the following sources: atmospheric precipitation in the area of the water table and the coastal catchment area; waters of the Hnoienets, Shklo, and Yaksha rivers; groundwaters of the Neogene aquifer complex, the mineralization of which is about 2700 mg/l. The pit was filled with water from the Hnoienets, Shklo, and Yaksha rivers in 2002–2006.

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[12] Rudko, G., Bondarenko, M., 2001. The technogenic ecological safety of the salt and sulphur minings of Lviv region (in Ukrainian with English summary). Proceedings of the Shevchenko Scientific Society, VII: 68–75.

[13] Kaminetska, B., Haydin, A., Dyakiv, V., 2012. Geoecological characteristic upland lakes in the area of influence Podorozhnenske sulfur career (in Ukrainian with English summary). Lviv University Bulletin. Geological Series, 26: 221–235.

According to the latest research, the water of Yavoriv Lake belongs to the kind that is considered clean, and salty[14]. Water mineralization in the surface zone stabilized at the level of 1.3 g/dm^3, and hydrogen sulphide is absent (Table 8). Further water desalination is possible after the completion of the intake facility on the Hnoienets River and the drainage of the Novy Yar reservoir, as provided for in the project. According to the data of the Lviv Department of Nature Protection, the water of man-made reservoirs - ponds on rivers in the area of operation of the former Yavoriv SME "Sirka" corresponds to the quality of natural waters of this region, and these reservoirs are used by the local population. Since sulphur mining was stopped 20 years ago, the territory has been reclaimed, and the quality of groundwater is satisfactory, there is no threat to transboundary groundwater. Groundwater of the Neogene aquifer has a naturally high content of sulphates associated with deposition in gypsum strata.

Table 8. Chemical composition of Yavoriv lake water (mg/dm^3)[15]

Depth, m	pH	Na^+	Ca^{2+}	Mg^{2+}	HCO_3^-	SO_4^{2-}	NO_3^-	P_2O_5	H_2S	NH_4^+	Mineralization
0	6,9	29,7	290	6,1	173	710	5,1	0,0	0	2,1	1248
5	7,5	29,5	310	2,4	175	759	5,1	0,0	0	1,7	1314
10	7,5	29,7	300	2,4	170	995	5,8	0,0	0	2,5	1538
20	7,3	32,4	308	1,2	168	948	5,7	1,1	0	1,8	1500
30	6,6	35,9	340	13,4	373	1502	6,8	17,2	20,2	8,4	2352
40	6,6	38,5	332	4,9	368	1546	8,8	17,8	24,8	9,3	2386
50	6,6	41,1	336	2,4	383	1333	9,5	18,2	21,7	8,7	2188
60	6,6	41,9	330	4,9	370	1332	17,7	12,1	20,7	7,6	2174
70	6,6	42,5	338	4,9	358	1571	19,1	13,9	22,7	7,9	2415
82 (bottom of the lake)	6,6	43,0	348	6,1	441	1308	16,1	33,1	28,4	17,3	2280
Shklo River flow into the lake	7,4	17,5	102	6,1	205	389	4,4	0,0	0	0,0	750
leakage from the lake	7,8	37	326	45	168	769	–	0,4	–	–	1377

Coal mining. The Lviv-Volyn coal basin is located in the northwest of Ukraine in the upper reaches of the Western Bug River and is the south-eastern part of the Lublin coal basin (Figure 13). Geologically, the basin is a mild monocline that gradually descends in the northwest direction. Carboniferous deposits

[14] Savchuk, L.V., Doskich, S.V., 2020. Territory revitalization of the spent Yazivsky and Nemyrivsky sulfur ore deposits (in Ukrainian with English summary). Scientific Notes of V.I. Vernadsky Taurida National University. Series: Technical Sciences, 31 (70), 4: 273–278. https://doi.org/10.32838/2663-5941/2020.4/41
[15] Ibid.

belong to the Lower and Middle Carboniferous strata, where up to 60 coal seams with a thickness of 0.5–1 m are concentrated. The depth of their occurrence is 300–1200 m[16].

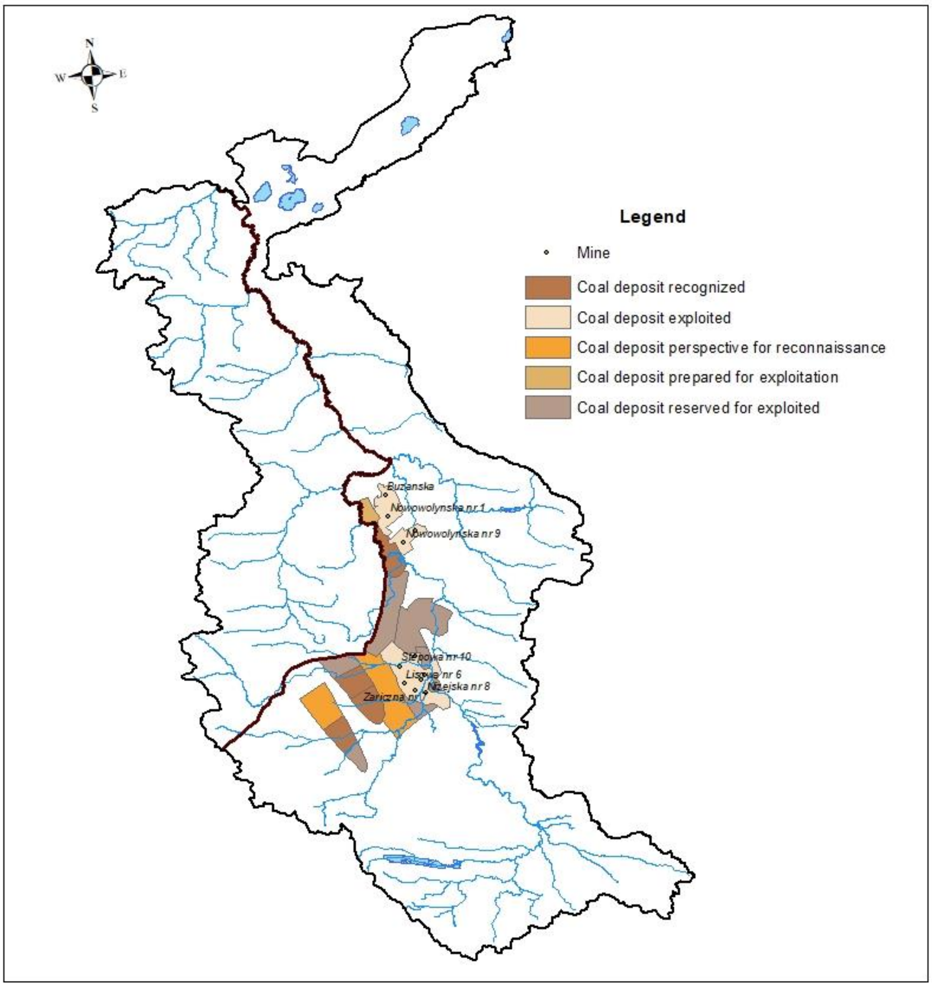

Figure 13. Location of coal mining areas within Bug river basin

The mining industry of the Lviv region within the cross-border pilot area is represented by the Chervonohrad coal-mining region. The state-owned enterprise operates six mines, which produce about 1.3 million tonnes of coal annually. Eighteen heaps from 12 mines and a gravity waste dump of the Chervonohrad Central Enrichment Factory are concentrated in the area. In the territory of the region, as a result of many years of coal mining, a large amount of coal-bearing rocks was brought to the surface of the earth and a significant amount of mine drainage was carried out. During the entire period of operation of the mines, 200 million m^3 of mine water with a mineralization of 6-8 and more g/l entered the earth's surface.

The main environmental problems of the territory are the deformation of the ground surface, which is accompanied by subsidence and flooding over mining operations; change in the seismicity of the territory, formation of landslides; soil pollution and changes in geochemical fields; pollution of surface, and

[16] Mineral resources of Ukraine, 2018. Editors: S.I. Prymushko, V.S. Labuzna, V.F. Velychko. Kyiv, State Geological Information Fund of Ukraine.

groundwater; pollution of the air and atmospheric precipitation; formation of man-made landscapes. Such exogenous processes can lead to the partial disappearance of small watercourses, the disappearance of old ones, and the formation of new ones in places of subsidence of the surface. Rivers into which polluted and mineralized mine waters are discharged lose the ability of watercourses to self-purify. Irreversible changes occur in the aeration zone, which can lead to disruption of ecosystems[17].

In the Chervonohrad coal-mining region, water from the pressure aquifer in the Upper Cretaceous deposits is used for domestic and drinking water supply. Even in the beginning of coal mining, the groundwater of the Upper Cretaceous deposits had good organoleptic indicators: clear, colourless, with a pleasant taste, fresh water with a dry residue of 0.3–0.7 g/dm^3, with the most frequent values of 0.4– 0.6 g/dm^3. The pH is close to neutral and varied between 6.4–8.6, more often between 7.1–7.6. The most often observed type of water was Ca-HCO_3 and Na-Ca-HCO_3. The content of HCO_3 — 360–744 mg/dm^3, Cl— 18–100 mg/dm^3, SO_4^{2-} — 0–49 mg/dm^3, Na — 36–230 mg/dm^3, K — 8–25 mg/dm^3, Ca — 16– 130 mg/dm^3, Mg — 2–47 mg/dm^3. There were no elements that did not meet the requirements of hygienic standards and control over the quality of drinking water[18].

Modern hydrochemical properties of the aquifer in the Upper Cretaceous deposits are determined by natural and man-made (coal mining, exploitation of water intakes of centralized water supply) factors. Hydrodynamic and hydrochemical conditions have changed in areas that have subsided as a result of hard coal mining. The leaching of rocks in heaps and sludge pits has created conditions for heavy metals to infiltrate into soil and aquifer. The recharge of the aquifer in the Upper Cretaceous sediments is mainly due to the infiltration of atmospheric precipitation through the layer of sediments that lie higher on watershed and valley slopes.

Groundwater pressures increase from the watershed to river channels, where they reach 20–30 m, depending on the thickness of Quaternary deposits and the colmatage zone. In the lowest situated places of the valleys, wells are overflowed, and the level is set to 3.0–3.5 m above the surface. With the deepening of the wells and the achievement of fracturing, the static levels increase, which indicates the flow of deep mineralized waters into the upper horizons. During the operation of water intakes and the emergence of a depression cones an overflow increases, which leads to certain changes in the chemical composition of water and an increased share of trace elements and various compounds reflecting the composition of deep deposits.

As a result of the operation of water intakes in the aquifer within the Chervonohrad coal-mining region, 6x6 km depression cones are formed (Pravdynskyi, Boryatinskyi water intakes). As a result, the

[17] Poberezhsky, A., Buchynska, I., Shevchuk, O., Mukan, T., 2019. Mining complex of the Lviv-Volyn coal basin and its impact on the ecosystem of the region (in Ukrainian with English summary). Geology & Geochemistry of Combustible Minerals, 3(180): 52–59 https://doi.org/10.15407/ggcm2019.03.052

[18] Havrylenko, K. S., Shtohryn, O. D., Shchepak, V. M., 1968. Groundwaters of the western regions of Ukraine (in Ukrainian). Kyiv, Naukova dumka.

Western Bug and Solokia rivers are transformed in the zone of influence of water intakes from the drainage zone into the groundwater recharge area. Within these depression cones are the pits of the Velikomostivska, Bendyuzka, Chervonohradska, Chervonohradska-1 and Velikomostivska No. 5 mines, the old tailings storage facility of the Central Enrichment Factory (CEF). Fluids infiltrating from these man-made objects can flow into the aquifer in the Upper Cretaceous deposits, which is used for domestic and drinking water supply[19].

According to the environmental condition, the mining regions of Ukraine can be divided into three groups: 1 – partial, 2 – significant, and 3 – critical deterioration of the environment. The main factors that determine the ecological condition of the mining regions of Ukraine are:

- violation of the geomechanical and hydrogeofiltration equilibrium of the rock massif due to mining operations with the extraction of large volumes of mineral raw materials and groundwater, the formation of water-permeable zones of man-made fracturing;
- accumulation of waste from mining and processing complexes;
- violation of the hydrogeological regime of the territory.

All other factors (development of dangerous geological processes, pollution of the surface environment, soil, ground- and surface water, reduction of biodiversity, etc.) are mostly derived from these three[20]. The Lviv-Volyn coal basin belongs to an area with a significantly deteriorated state, and partly even to an area with a critical state of the environment. However, due to the direction of the flows, the harmful effect of pollutants carried by water from heaps, sludge reservoirs, and mine water sediments does not extend to the transboundary territory.

4. Identification of quantitative resource pressures

The recorded groundwater abstraction was used to map the pressure on the quantitative groundwater status. For this purpose, the available information on the size of the abstraction on both sides of the border was used. The data concerned both water supply intakes and industrial installations. During the data collection, a clear disproportion of information available in the Polish and Ukrainian parts of the area was found. While in Poland it was possible to obtain data also for small intakes (capacity below 100 m^3/d), in the Ukrainian part the available data concerned mainly the largest intakes (capacity above 1000 m^3/d). As a result, the spatial distribution of groundwater abstraction is clearly uneven (Figure 14). However, this does not result from the density of the settlement network and the demand for water, but

[19] Buchatska, H.M., 2011. Ecological state of the aquifer in the Upper Cretaceous sediments of the Chervonohrad mining district (in Ukrainian with English summary). Collection of scientific works of the Institute of Geological Sciences of the National Academy of Sciences of Ukraine, 4: 47–50.

[20] Rudko, H., Yakovlev, Ye., 2020. Post-mining of the Ukraine's mining regions as a new direction for the environmentally safe use of mineral resources (in Ukrainian with English summary). Mineral resources of Ukraine, 3: 37–44. https://doi.org/10.31996/mru.2020.3.37-44

from the different legal conditions in both countries determining the management of information on the volume of abstraction. Based solely on official data on abstraction, the analysis of pressure on the quantitative status of groundwater took into account the operation of 712 intakes, whose total recharge amounted to 237,774.14 m^3/d, of which 31,825.24 m^3/d occurs in Poland, and 205,948 9 m^3/d – in Ukraine.

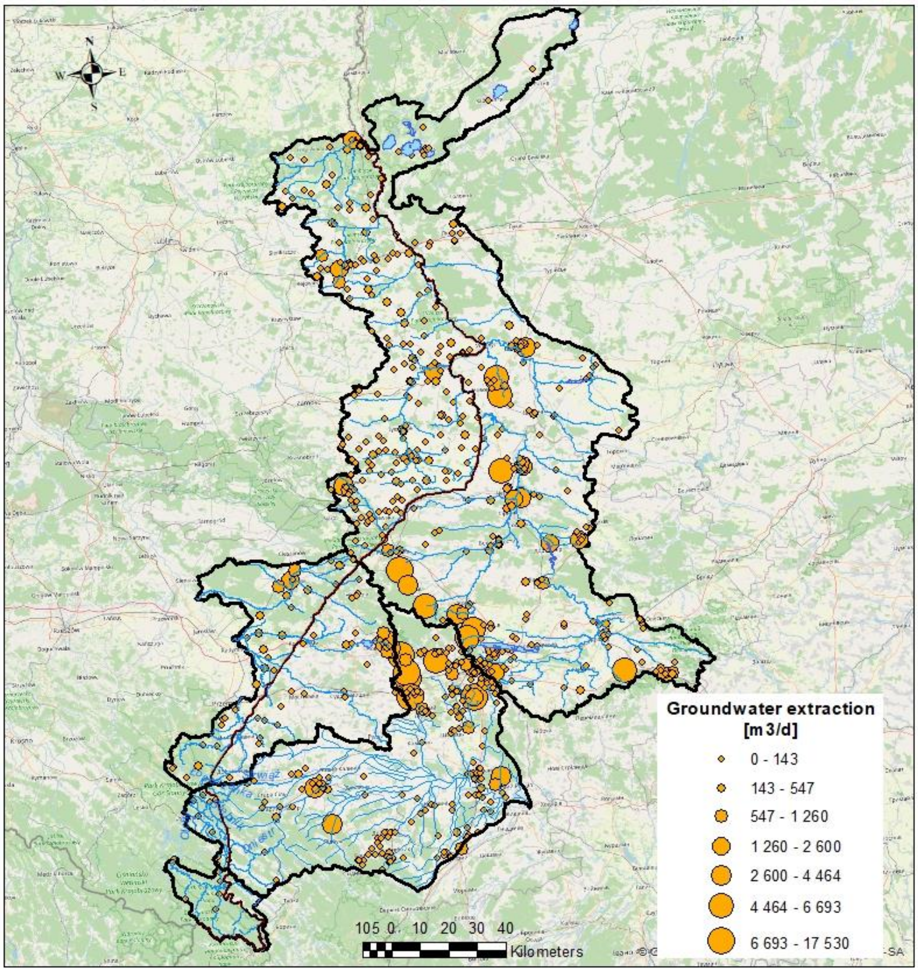

Figure 14. Spatial distribution of registered groundwater abstraction

In the division into catchment areas of the Bug, San and Dniester rivers, the distribution of registered groundwater abstraction varies (Table 11). The analysis of the data shows that the maximum value of the registered groundwater abstraction occurs in the Bug catchment area - 123,570.2 m^3/d, especially on the Ukrainian side (80%). In the Dniester catchment, the abstraction is 95,812.03 m^3/d, of which 134.39 m^3/d is in Poland and 95,677.64 m^3/d in Ukraine. The lowest value was recorded in the San catchment – 18,391.93 m^3/d, of which 6,811.66 m^3/d is in Poland and 11,580.27 m^3/d in Ukraine. The differentiation of the abstraction results from the density of the settlement network and the percentage of the population using the group supply system.

Table 11. Groundwater abstraction by catchment basin as of 2018-2020

Catchment	Registered abstraction of groundwater, m^3/d	
	Poland	Ukraine
Bug	24,879.19	98,691.01
San	6,811.66	11,580.27
Dniester	134.39	95,677.64
Total	31,825.24	205,948.9

The issue of unregistered abstraction required a separate approach. This problem, although with different intensity, occurs on both sides of the border and should be analysed. The actual amount of groundwater abstraction is difficult to determine and can only be estimated with some approximation. This is due to the fact that a significant part of the consumption eludes official statistical summaries, which contain data only on intakes supplying public water supply networks and industrial installations. However, there remains the problem of individual intakes, which are usually not metered and their work is not reported in any way. This is especially true in rural areas, where intakes of this type are commonly used for economic purposes and irrigation of crops. Although individual intakes generally work with low efficiency, together they are an important component. The method of estimating unregistered abstraction is described in detail in the 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). The information obtained from the border administrative units on the structure of the water supply system showed significant differences in the development of the water supply network on both sides of the border. On the Polish side, in nearly half of the communes (14 out of 31), the percentage of the population using the group water supply system exceeds 90%, and only in two communes this percentage is lower than 10%. On average, in communes on the Polish side, 75.3% of the total population uses the water supply network. On the Ukrainian side, the development of the water supply network is definitely lower. In the majority of communes (13 out of 24), the percentage of the population connected to the water supply system does not exceed 10%, and only in one commune does it exceed 75%. On average, in the communes on the Ukrainian side, only 16.3% of the population uses group water supply. Against this background, the data on the average water consumption from the network supply system per capita looks interesting. Data obtained for communes on the Polish side of the border indicate that this value is usually in the range of 0.04 - 0.17 m^3/d/person, and the average value of the demand is 0.11 m^3/d/person. Meanwhile, on the Ukrainian side, the average value of demand for water is almost twice as high and amounts to 0.18 m3/d/person, while in most communes it is a value within a narrow range of 0.2 - 0.23 m^3/d/person.

It should be noted that the quoted differences in water consumption do not result from the diversified demand for water per capita, but only testify to a different scale of the hidden abstraction problem, for which individual intakes are responsible. The actual demand for water per capita remains unknown and must be assumed a priori in order to take into account the pressure of unregistered abstraction in the analysis. The demand at the level of 0.4 m3/d/person was considered a safe value, i.e. a value approximately twice as high as the maximum registered consumption in both the Polish and Ukrainian parts of the area. Thanks to the applied methodology, the distribution of unregistered abstraction in the area of particular importance for possible transboundary impacts was obtained (Figure 15).

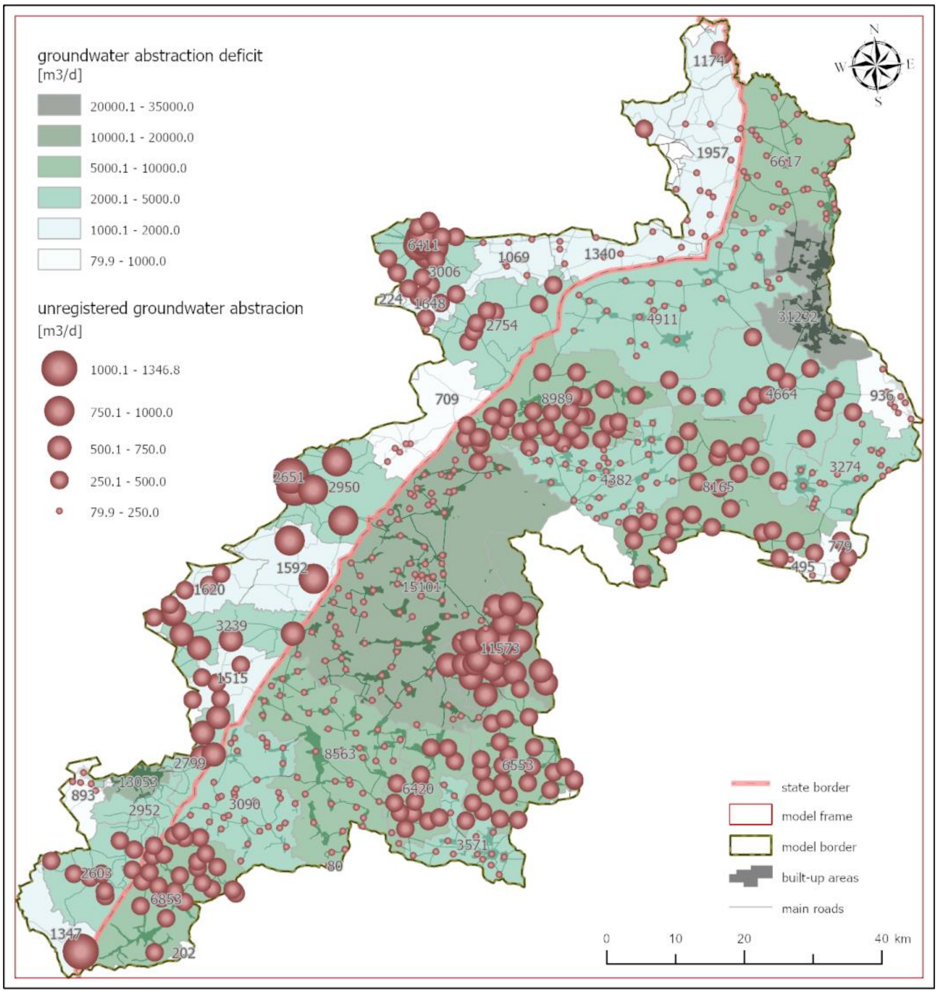

Figure 15. Distribution of unregistered abstraction within the area of possible transboundary impacts

5. Assessment of quantitative pressure on groundwater status

The aim of the quantitative pressure assessment was to determine the current and maximum possible impact on the groundwater status at the level of groundwater resources available for management. This task was carried out on a numerical hydrodynamic model created within the EU-Waterres project. A detailed description of the model is presented in the 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). This model made it possible to simulate the abstraction of groundwater at different pressure variants of the studied aquifer system. The planned simulations made it possible to assess the impact of the current and maximum permissible groundwater abstraction on the hydrodynamic condition of the system.

The impact of the current pressure of the studied aquifer system was determined on the basis of registered and estimated unregistered abstraction from individual intakes, which are usually not metered and their work is not reported in any way. Although individual intakes usually work with low efficiency, together they constitute an important component of the water balance, which cannot be neglected in assessing the impact of groundwater intake on the hydrodynamic condition of the system. Unregistered consumption was estimated at 0.25 m^3/d/person - the average value of water demand in most communes on the Ukrainian side. Registered abstraction includes exploitation of groundwater in currently functioning intakes (1,128 wells) and concerns mainly K2 aquifer or combined Qal-K2 (70% wells), other aquifers are Qal, N1, Qal-N1. Spatial diversification of the volume of exploitation at the average level over the last 4 years is described in detail in Chapter 4 *Identification of quantitative resource pressures*. Taking into account unregistered abstraction, it was shown that the actual abstraction of groundwater is 122,557.5 m^3/d and is 1.4 times higher than the registered abstraction.

A characteristic feature of the Polish part of the study area is the dominance of groundwater intakes with abstractions generally below 1000 m^3/d. Taking into account only the consumption recorded at this level, no drawdown cones are observed on a scale noticeable on the regional model. Only a group of intakes in the area of Tomaszów Lubelski with a total groundwater abstraction from K2 aquifer in the size of approx. 4000 m^3/d generates drawdown cones with a maximum lowering of the groundwater table to 3 m. In the Ukrainian part, the exploitation of groundwater is concentrated in large municipal intakes with volumes at the level of 5000-8000 m^3/d. This exploitation results in the creation of several drawdown cones in K2 aquifer with a size of 5-25 m.

With the additional pressure of the aquifer system by unregistered abstraction at the level of 0.25 m^3/d/person, the scale of the actual impact becomes real (Figure 16). The previously identified drawdown cones are joined by others, mainly in the San river basin in the area of the communes with the highest population density - the Przemyśl agglomeration (Poland) and the communes of Sudovovyshnianska and Dobromylska (Ukraine). The indicated communes on the Ukrainian side are not among the most populous, rather average, but in combination with the low resourcefulness of the aquifer system in their area, they are at risk of lowering the groundwater table below 2 m, with maximum values reaching even 16 m in the villages of Makunin, Dmytrowyczy, Dydiatyci. In the Bug catchment, additional pressure manifests itself in the extension of the range and size of depressions of the already existing drawdown cones in the area of large municipal intakes.

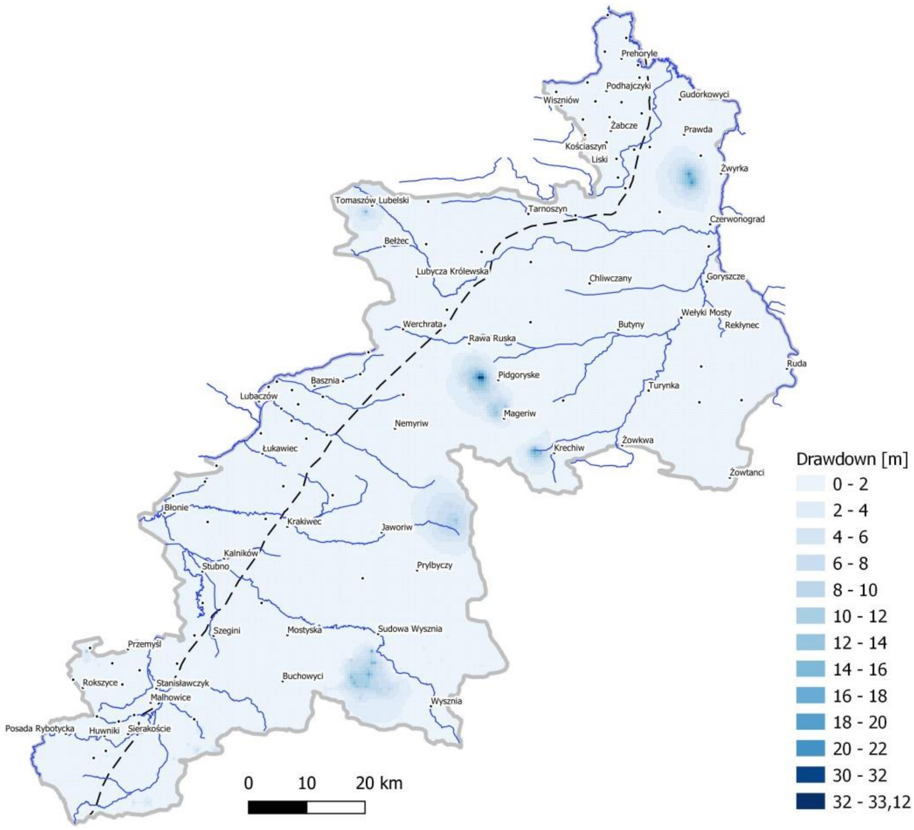

Figure 16. Simulated of groundwater drawdown with exploitation at the level from 2018-2021[21]

The analysis of the impact of the current abstraction of groundwater in terms of the balance showed that in the Polish part of the study area abstraction accounts for 5.8% of groundwater supply by atmospheric precipitation, in Ukraine - about 10.3%. The changes caused concern the increased infiltration of surface waters into the aquifer system (4.0% - in Poland and 21.9% - in Ukraine) and the deepening reduction of surface water supply (3.7% - in Poland and 6.1% - in Ukraine). The combination of these two effects results in the loss of river water resources. There are no significant changes in the transboundary exchange of groundwater compared to the natural state, these values are insignificant at the level of 0.5-0.6%.

The simulation was carried out at the level of the maximum permissible groundwater exploitation, which is understood as the resources available for development. According to the definition given in the WFD, the resources available for development are understood as the difference between the renewable resources of the groundwater system and the size of the river baseflow. In practice, this expression means the volume of water available for management, which is the amount of groundwater that can be collected from the hydrogeological system constituting the balance area - without worsening their chemical status and maintaining the desired condition of groundwater-dependent ecosystems.

[21] taking into account the registered consumption and the estimated unregistered consumption at the level of 0.25 m^3/d/person

The main assumptions of the conducted simulation of groundwater abstraction at the level of resources available to management include:

1. The reference point was the piezometric surface obtained in the simulation, taking into account the registered and unregistered abstraction in the amount of 0.25 m^3/d/person;
2. The following areas were excluded from the abstraction simulation (the aquifer system was not under pressure):

- Surroundings (1 km buffer) of model blocks with condition II - Well condition, by means of which the recorded groundwater abstraction was mapped;
- Surrounding (0.5 km buffer) centroids of virtual shots with unregistered abstraction;
- National parks;
- Reserves;
- Groundwater dependent ecosystems;
- Natura 2000 areas.

In blocks located outside the excluded areas, the maximum possible abstraction was simulated so that the groundwater table depression calculated from the piezometric surface in the baseline simulation described above (current registered + unregistered abstraction at the level of 0.25 m3/d/person) did not exceed the regional value of 2, 0 m, and locally, in the vicinity of large intakes - a maximum of 4 m.
The value of the maximum abstraction available for management obtained in this way was then distributed to groundwater abstraction points, which were mapped in the model using the Well condition. The results of the simulation of groundwater abstraction at the level of resources available for development are shown in Figure 17.

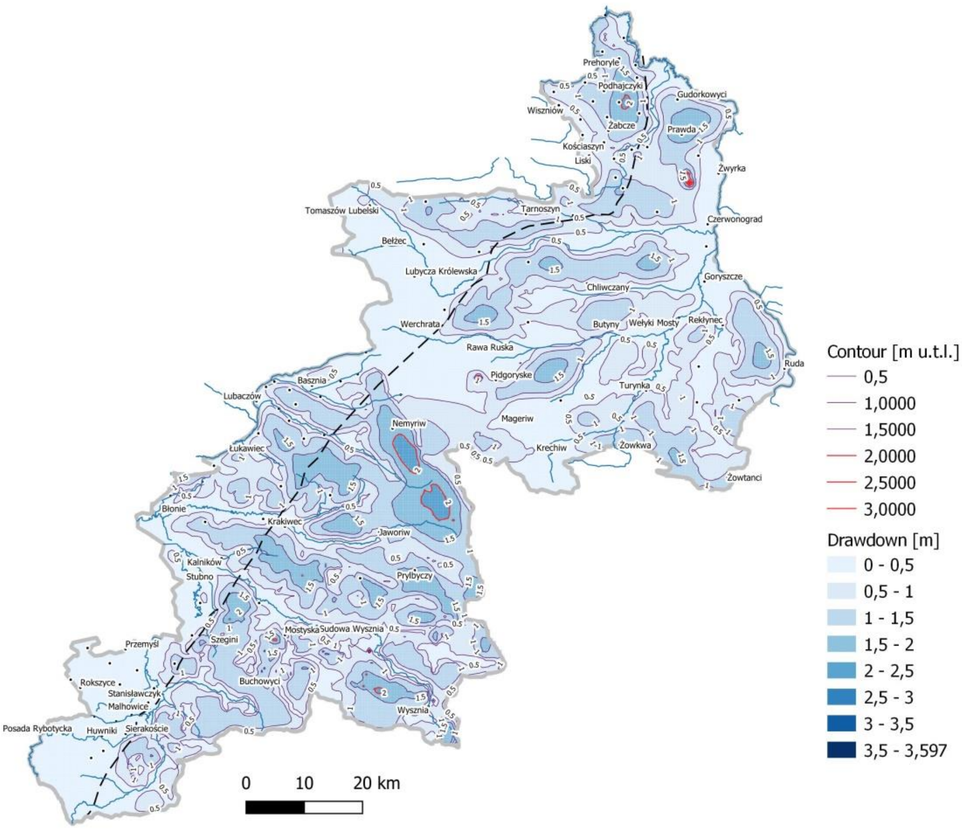

Figure 17. Simulated groundwater drawdown at the level of resources available for management

This scenario shows the possible regional, not local, lowering of the groundwater table at the maximum permissible pressure of the aquifer system with water abstraction. The result of the calculations is consistent with the assumed regularity - the greatest sensitivity to the lowering of the groundwater table is found in areas with low natural abundance of the aquifer system combined with significant groundwater abstraction. The following regularities can be traced in the obtained spatial distribution:

- in general, the catchment of the San, compared to the catchment of the Bug, is more sensitive to the lowering of the groundwater table, mainly due to the low natural abundance of the aquifer system;
- areas with a regional lowering of the groundwater table exceeding 1.0 m are located in non-valley zones of rivers, constituting groundwater drainage axes in the studied system. The exception is Roztocze - the watershed zone between the underground catchment of the Bug and the catchment of the San and the area of the Carpathian mountain overthrust, which were not included in the simulation of abstraction due to belonging to protected areas;
- areas with the greatest lowering of the groundwater table exceeding 2.0 m are located in areas where two unfavourable factors coexist - low natural abundance of the aquifer system and concentration of groundwater intakes.

It was recognized that the regional lowering of the groundwater table, when exploited at the level of resources available for management, may be an appropriate indicator for assessing the sensitivity of the aquifer system to quantitative pressure on groundwater status. Four classes are proposed:

- negligible sensitivity of the aquifer system to quantitative pressure – lowering the groundwater table below 0.5 m;
- low sensitivity - lowering the groundwater table by 0.5-1 m;
- significant sensitivity - lowering the groundwater table by 1-2 m;
- high sensitivity - lowering the groundwater table by more than 2 m.

By catchment, the analysis of the sensitivity of the aquifer system to quantitative pressure showed significant differences between the Bug and the San. In the San catchment area, 54% of the area is marked by a significant sensitivity of the aquifer system to quantitative pressure, and 3% - high. Meanwhile, in the catchment area of the Bug, only 16% of the area is sensitive to quantitative pressure, and 0.2% - high.

In terms of administrative units, areas with high sensitivity of the aquifer system to quantitative pressure are located in the following localities:

- Poland: Dołhobyczów;
- Ukraine: Mostyska (OTG Mostyska), Melnyky (OTG Yavorivska), Shysherowychy, Dydiatychy, Dmytrovychy, Makuniv (OTG Sudovovyshnianska), Starychi (OTG Novoiavorivska), Zamok (OTG Dobrosynsko-Maherivska), Savchym (OTG Sokalska).

In the first place, a groundwater protection plan should be developed for these localities.

6. Assessment of anthropogenic pressure on chemical status of groundwater

The impact of anthropopressure on the chemical status of groundwater is generally resolved in two ways: the impact of diffuse and point pollution sources. In this study, pressure from diffuse sources was calculated on the basis of three indicators - agricultural, urban-industrial and municipal pressure. Pressure from point sources took into account the presence of potentially polluting sites - landfills and municipal and industrial sewage treatment plants. On the basis of partial indicators, the total pressure was calculated, which is the assumption of the assessment to which this chapter is devoted. The assessment of cumulative pressure is often identified with the assessment of the risk associated with potential groundwater pollution from point and diffusion sources[22]. The basic dataset for calculating the cumulative pressure is CORINE 2018[23]. The CLC scale is 1:100,000, which corresponds to a calculation grid of 1 km. For each CORINE land use class at level 3, it is assumed that the load coefficient of water pollution is proportional to the organic

[22] Daly, D., Dassargues, A., Drew, D., Dunne, S., Goldscheider, N., Neale, S., Popescu I.C., Zwahlen, F., 2002. Main concepts of the "European approach" to karstgroundwatervulnerability assessment and mapping. *Hydrogeology Journal*, 10/2: 340–345.

[23] Corine Land Cover Poland (CLC), 2018. https://clc.gios.gov.pl/arcgis/services/CLC/CLC2018/MapServer/WMSServer

emission coefficients for the given land use type in CORINE. The emission factors for nitrogen and phosphorus are the most widely used. Based on a review of the literature, it was determined that load coefficient of 0 to 1 should be appointed to each pixel on the map depending on the potential pollution hazard[24]. These assigned values are empirical, and the largest values are commonly present in zones of mining, landfills, waste dump sites, heavy industry or irrigated areas with intensive crop production, as these can have a high impact on groundwater quality deterioration as diffuse pollution sources[25]. Load coefficients (hazard indices) for individual CORINE's values were taken from the EU project CC-WARE study[26]. In general, the following hazard indices for diffusion pollutants were assumed, as presented in.

Table 9. Categorisations of the hazard indices of diffuse pollutants

Land use category	Hazard indices
Agricultural land	0,8
Anthropogenic land	0,9
Urban areas with a low level of sewage systems (60-100 people/km2 do not use group sewage systems)	1,0
Urban areas with a negligible level of sewage system (more than 100 people/km2 do not use the group sewage system)	2,0

Hazard indices for point sources of pollution were determined using the popular rank method. Two indicators were taken into account - the presence of landfills and municipal and industrial sewage treatment plants. For both indicators, the maximum degree of significance was adopted, i.e. the weight of 1, due to the significant role of potential pollutants in the migration process. Then, within each indicator, classes of values of the considered parameter were distinguished and assigned a rank, i.e. a specific score on a scale of 0.5 to 1. The higher the rank, the greater the risk of contamination. The following ranks were adopted for individual indicators (Table 10).

Table 10. Categorisations of the hazard indices of point pollutants

“Landfill” indicator	**Ran**k	"W**astewater treatment plants"** i**ndica**tor	**Ran**k
Non-hazardous facility	0,5	Facility using various treatment methods (biological, chemical, mechanical)	0,5
Hazardous facility	1,0	A facility using only a mechanical treatment method	1,0

The final rating is based on the hazard indicators of point pollutants, which is the sum of the products of weights and ranks of individual indicators.

The cumulative pressure rating (GW hazard) within each computational cluster was estimated by the formula:

[24] Stevanović, Z., Marinović, V., 2020. A methodology for assessing the pressures on transboundary groundwater quantity and quality – experiences from the Dinaric karst. *Geologia Croatica,* 73-2: 107-118
[25] Ibid.
[26] Cencur, C.,B., 2014. CCWARE Mitigating vulnerability of water resources under climate change, WP3, Annual Report.

$$GW\ hazard = ((\sum HI_i \times F) + (\sum W \times R))/n,$$

where:

HI_i – hazard indicators of diffuse pollutants for the land use categories presented in Tab.11;

F – share in the computational cluster area of a given land use category,

W – point impact index weight;

R – rank of point impact index;

n – number of indicators included in the assessment in a given cluster.

As a result, a grid layer was created representing the spatial distribution of GW hazard values - an indicator of the assessment of total anthropopressure (Figure 18). The intensity of total anthropopression was validated on the basis of the proposed division of GW hazard into 6 classes (Table 11) by Stevanovich[27].

Table 11. Classification of the value of the GW hazard indicator

GW hazard classes	Index
No hazard	0 – 0,10
Very Low	0,11 – 0,20
Low	0,21 – 0,30
Average	0,31 – 0,50
High	0,51 – 0,70
Very High	0,71 – 1,00

[27] Stevanović, Z., Marinović, V., 2020. A methodology for assessing the pressures on transboundary groundwater quantity and quality – experiences from the Dinaric karst. *Geologia Croatica,* 73-2: 107-118

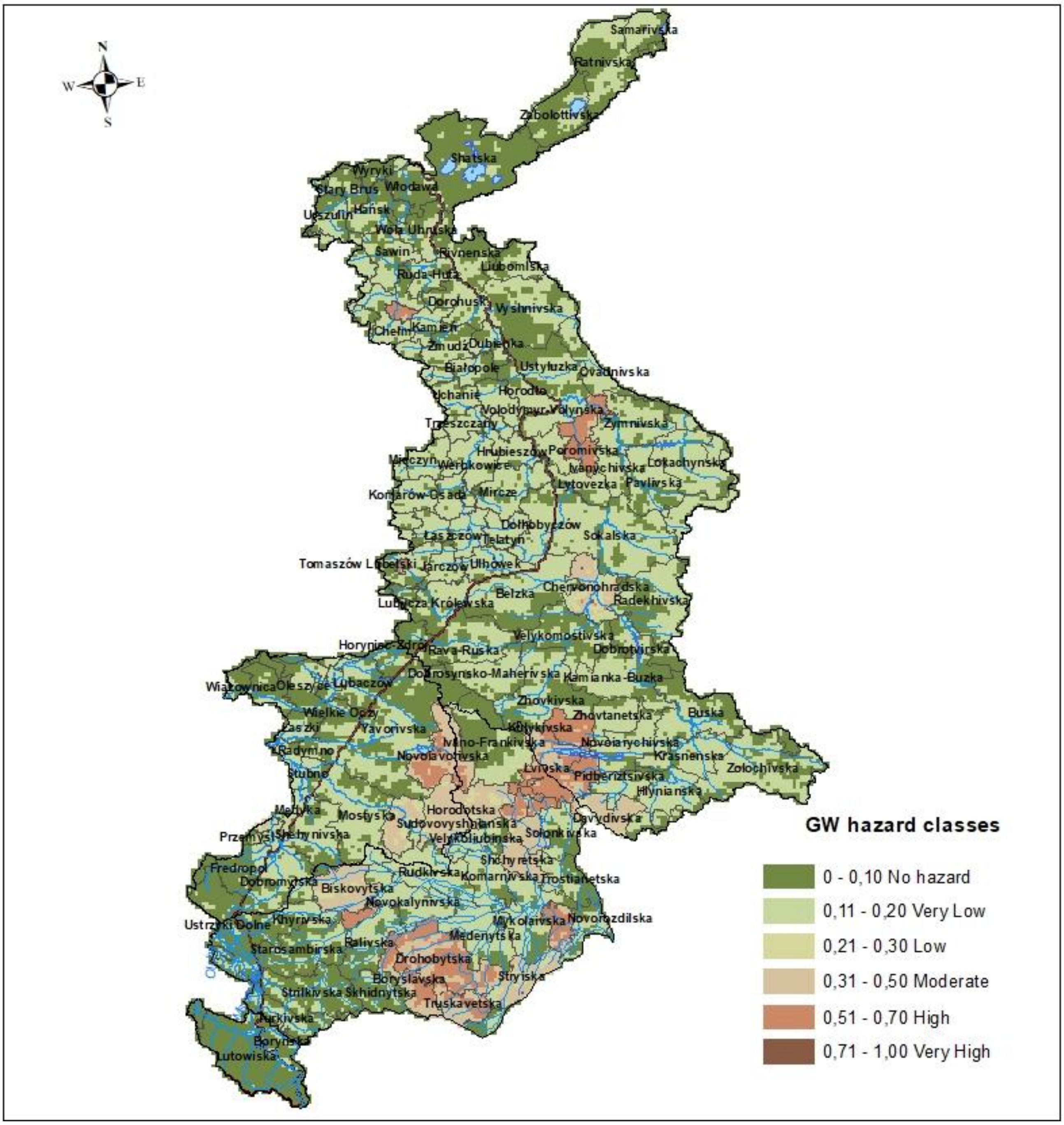

Figure 18. Groundwater hazard – cumulative anthropopressure

The highest values of GW hazard (index above 0.51) were obtained in territorial communities on the Ukrainian side, with high population density, a negligible level of development of the sewage collection system (over 100 people/km^2 do not use the group sewage system) and numerous point pollution sources, mainly landfills hazardous waste and sewage treatment plants. These communities include: Volodymyr-Volynska, Novovolynska, Kulykivska, Lvivska, Zymnovodivska, Sokilnytska, Obroshynska, Novoiavorivska, Rozvadivska, Sambirska, Drohobytska, Boryslavska and Truskavetska. On the Polish side, the highest GW hazard values (index above 0.51) were obtained in the most urbanized communes - Chełm and Tomaszów

Lubelski. The average GW hazard (index within 0.31-0.50) is most often observed where two factors coexist - densely populated areas with a low level of development of the sewage collection system and a high (over 0.5) indicator of agricultural pressure. These areas are mostly on the Ukrainian side - territorial clusters: Chervonohradska, Horodotska, Davydivska, Pustomytivska, Shchyretska, Sudovovyshnianska, Stryiska and Biskovytska. GW hazard with an index in the range of 0.21-0.30 is dominant in the study area and characteristic of the Bug catchment area. Against this background, the data on GW hazard broken down by catchments look interesting (Table 12, Table 13 and Table 14).

Table 12. GW hazard in the catchment area of the Bug by classes

Poland		Ukraine	
GW hazard index	% of the area	GW hazard index	% of the area
0 – 0,10 No hazard	32,59%	0 – 0,10 No hazard	40,64%
0,11-0,20 Very Low	65,83%	0,11-0,20 Very Low	51,14%
0,21-0,30 Low	0,59%	0,21-0,30 Low	1,12%
0,31-0,50 Average	0,18%	0,31-0,50 Average	3,38%
0,51-0,70 High	0,81%	0,51-0,70 High	3,62%
0,71-1,00 Very High	0%	0,71-1,00 Very High	0,10%

Table 13. GW hazard in the San basin by class

Poland		Ukraine	
GW hazard index	% of the area	GW hazard index	% of the area
0 – 0,10 No hazard	68,32%	0 – 0,10 No hazard	34,44%
0,11-0,20 Very Low	30,40%	0,11-0,20 Very Low	43,67%
0,21-0,30 Low	0,83%	0,21-0,30 Low	3,43%
0,31-0,50 Average	0,45%	0,31-0,50 Average	14,74%
0,51-0,70 High	0%	0,51-0,70 High	3,69%
0,71-1,00 Very High	0%	0,71-1,00 Very High	0,03%

Table 14. GW hazard in the Dniester catchment by class

Poland		Ukraine	
GW hazard index	% of the area	GW hazard index	% of the area
0 – 0,10 No hazard	75,51%	0 – 0,10 No hazard	29,41%
0,11-0,20 Very Low	24,15%	0,11-0,20 Very Low	36,65%
0,21-0,30 Low	0,34%	0,21-0,30 Low	2,68%
0,31-0,50 Average	0%	0,31-0,50 Average	12,86%
0,51-0,70 High	0%	0,51-0,70 High	12,23%
0,71-1,00 Very High	0%	0,71-1,00 Very High	0,17%

The analysis of data on GW hazard in individual catchments showed significant differences on both sides of the border. On the Polish side, a lower level of total anthropopressure on the chemical status of groundwater is generally observed. In the catchments of the San and the Dniester, almost 75% of the area is classified as No Hazard, while in the remaining area, the pressure is very low. The Bug catchment area is dominated by areas with very low pressure with a significant share (1/3 of the area) of areas with no hazard. On the Ukrainian side, areas with very low pressure and No hazard predominate, compared to areas with significant pressure. The largest share of areas with high GW hazard (index above 0.70) was estimated in the Dniester catchment – 12.4%.

7. Assessment of the impact of anthropopressure on the qualitative state of groundwater

Several technical reports have been prepared at EU level to help harmonize approaches and procedures for water quality pressure and risk assessment. An example is the report prepared by the Working Group on Groundwater (GW WG) in 2003[28]. These guidelines are widely used in the development of River Basin Management Plans in accordance with the requirements of the WFD. Currently, a joint international management plan (the RBMP) has not been developed for the cross-border catchments of the Polish-Ukrainian research area, as is the case for the Danube catchment adopted by the International Commission for the Protection of the Danube River (ICPDR) in 2010[29] or the Sava river, adopted by the International Sava River Basin Commission (ISRBS) in 2014[30]. In this study, the above guidelines were taken into account so that the results obtained could serve as a precursor to future joint management plans.

The assessment of the impact of anthropopressure on the qualitative state of groundwater is derived from two parameters - groundwater vulnerability and hazard according to diffuse and point pollution sources (detailed description in Chapter 6 *Assessment of anthropogenic pressure on chemical status of groundwater*). In the most recent decades, vulnerability assessment of groundwater and aquifers has become a necessary tool for planning and managing groundwater resources. In combination with hazard maps, vulnerability maps point to endangered areas of special significance. In other words, the risk of pollution will depend on both, the potential pollutants and the vulnerability of the aquifers. Low groundwater vulnerability can minimize the impact of a high degree of hazards. Conversely, in the absence of anthropogenic activities in a catchment area with a high degree of vulnerability, the risk may be negligible.

Within the pilot area of the Polish-Ukrainian territory, we quantified the groundwater vulnerability using the modified Bindemann formula for calculating the time of water infiltration through the aeration zone[31]:

[28] GW WG, 2003. WFD Pressures and Impacts Assessment Methodology: Guidance on pressures and impacts methodology. Paper by the Working Group on Groundwater and Working Group on Characterisation and Reporting. Guidance document no. GW4. WFD Ireland.
[29] ICPDR, 2010. Danube River Basin Management Plan, Vienna Austria, www.icpdr.org
[30] ISRBS, 2014. Sava River Basin Management Plan, Zagreb, Croatia, www.savacommisison.org
[31] Macioszczyk, T. (1999). Czas przesączania pionowego wody jako wskaźnik stopnia ekranowania warstw wodonośnych (in Polish). Przegląd Geologiczny, 47(8), 731–736. Retrieved from https://geojournals.pgi.gov.pl/pg/article/view/15897/13324.

$$t\frac{m \times W_0}{\sqrt[3]{i^2 \times k_z}}$$

where

t – is infiltration time of precipitation through the aeration zone, days;

m – thickness of the aeration zone, m;

W_0 – volumetric moisture of sediments in the aeration zone,

i –annual effective infiltration, $i = P \times k*$, m/day (where *P* – is precipitation indicator, m/day; *k** – coefficient of effective infiltration);

k_z –vertical infiltration coefficient of the aeration zone, m/day.

The values of volumetric moisture (*Wo*), effective infiltration coefficients (*k**), and vertical infiltration of the aeration zone (k_z), which depend on the lithological composition of the aeration zone, are taken from Witczak and Żurek[32].

Precipitation indicator *P* for individual TGR was calculated according to the site "Meteopost. Weather statistics. Climate data by year and month" (https://meteopost.com/weather/climate/). For the Bug and San River basins, it is 0.00196, and for the Dniester basin, it is 0.00207 m/day.

In the process of fulfilling the project tasks, the following vulnerability classification was adopted based on the time of pollution migration from the surface (Table 15).

Table 15. Categorizations of the groundwater vulnerability

Time of pollution migration from the surface, years	GW Vulnerability class	**Vulnerability Index**
< 5	Very high	5
5-25	High	4
25-50	Average	3
50-100	Low	2
>100	Very low	1

Figure 19 shows the results of the assessment of the groundwater vulnerability in the Polish-Ukrainian border area.

[32] Witczak, S.& Żurek, A. (1994). Wykorzystanie map glebowo-rolniczych w ocenie ochronnej roli gleb dla wód podziemnych (in Polish). [W:] Kleczkowski A.S. (red.) - Metodyczne podstawy ochrony wód podziemnych, AGH: 155–180.

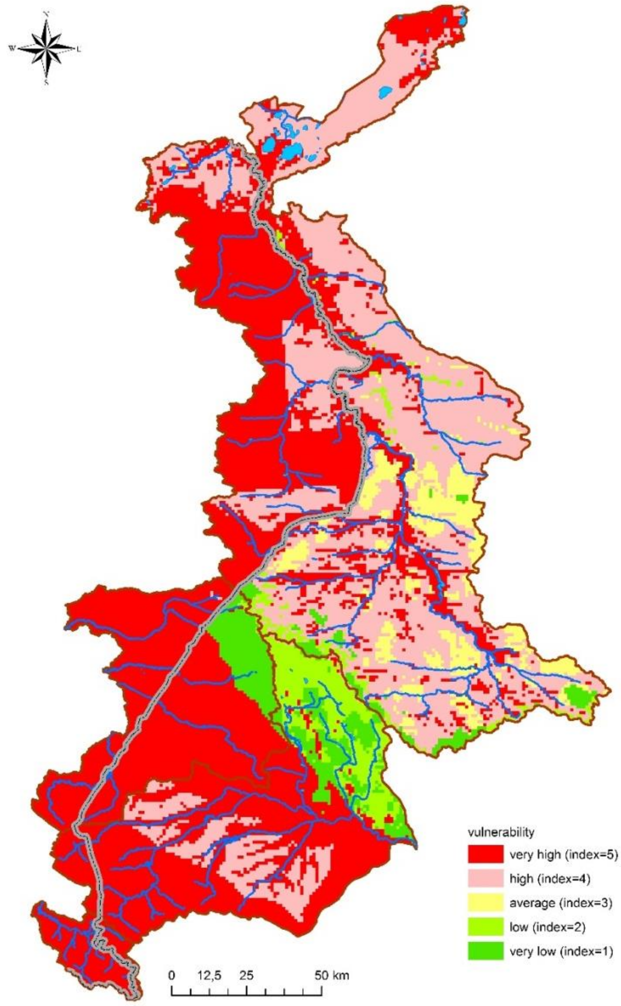

Figure 19. The groundwater vulnerability map of the Bug, San and Dniester Transboundary River Basins

Unconfined groundwater table makes the aquifer the most vulnerable. It is widespread in the river valleys of the Dniester and the San with their tributaries within the Carpathian Foredeep. In these catchments the groundwater table lies close to the surface, and is not covered by thick impermeable layers.

Confined aquifers of the Upper Cretaceous (K2) and Lower Neogene (N1) in the study area, are characterized by varying degree of vulnerability. The Upper Cretaceous aquifer (K2) is less vulnerable, which is of the greatest importance for meeting consumer needs in the transboundary area and covers the entire Bug TGR area from the Polissia Lowland in the north to the Podillia Upland in the south. It should be noted that groundwater of this horizon in the Polish part of the cross-border area is more vulnerable - here the horizon corresponds to the categories of "very high" and "high" vulnerability. In the Ukrainian part of the study area, the Upper Cretaceous aquifer is characterized by somewhat better natural hydrogeological conditions (higher aquifer thickness, presence of a "clogging zone"). There is a tendency for vulnerability to decrease from north to south: from very high in Polissia to high and medium in Volyn-Podillia. On the slopes of Roztochia, groundwater of the Upper Cretaceous horizon (K2) is sufficiently protected (very low vulnerability). However, in this region, the role of the MUA is taken over by the Lower Neogene aquifer (N1), which lies hypsometrically higher. In fact, the Lower Neogene aquifer (N1), which has a limited distribution on the slopes of the Western Bug and San Rivers watershed within the Roztochia Upland, is the least vulnerable to pollution compared to the others.

In the next stage, the groundwater vulnerability map and hazards map were combined, because the risk of pollution will depend on both the potential diffuse pollutants and the vulnerability of the aquifers and groundwater. For example, the low degree of groundwater vulnerability can increase risk due to diffuse pollution in the same GW body. In contrast, if there are no human activities taking place in the vulnerable catchment area, the risk can still be low. The risk mapping methodology implies the multiplication of each pixel from the vulnerability map with the corresponding hazard map pixel, resulting in a proportional index of risk (Table 16):

GW Risk = Index hazard x Index GW vulnerability

Table 16. Categorizations of the groundwater risk

GW risk classes	GW risk index
No risk	0,0 - 0,5
Very low	0,51 - 1,0
Low	1,1 - 1,5
Average	1,51 - 2,0
High	2,1 - 2,5
Very high	2,51 - 3,9

In general, the first two categories could be considered as “no pressure”, the following two as “potentially under pressure”, and the last two as “under pressure”. Depending on the % of the surface which the designated risk categories cover, each of the studied GWB could be proclaimed at risk or not.

Figure 20 shows the results of the assessment of the groundwater risk in the Polish-Ukrainian border area.

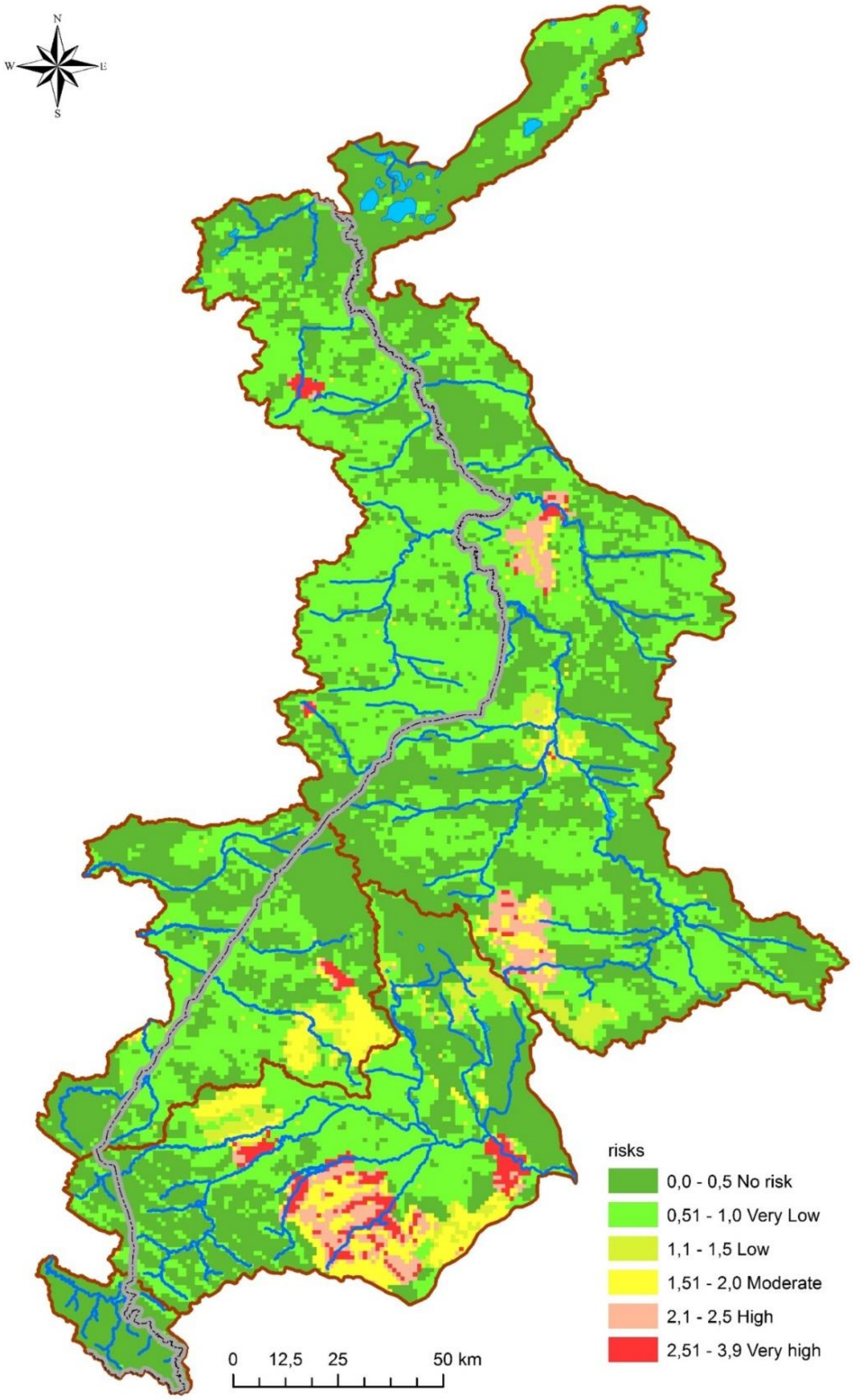

Figure 20. Map of Groundwater Risks

It can be seen from the map that the distribution of hazards caused by anthropopression has a significant influence on the risk assessment: the areas of significant hazards, described in Chapter 6 *Assessment of anthropogenic pressure on chemical status of groundwater*, remain in the zones of high pollution risks. However, a low degree of vulnerability often mitigates the risks from the hazard.

Roztochia zone is a clear example of the area where the high hazard of anthropopression is levelled by the low vulnerability of the aquifer of Miocene sediments, as a result of which the degree of risk is significantly reduced.

The tendency to level the hazard of pollution due to low vulnerability of aquifers is also observed in the territorial communities of Volodymyr-Volynska, Novovolynska, Kulikivska, Lvivska, Zymnovodivska, Sokilnytska, Obrosynska, Novoiavorivska, Rozvadivska, Sambirska, Drohobytska, Boryslavska, and Truskavetska on the part of Ukraine and in the most urbanized communes of Poland – Chełm and Tomaszów Lubelski.

On the other hand, as evidenced by the results of the assessment and development of the risk map, large areas of very vulnerable unconfined aquifers (Figure 19) do not fall into the zone of significant risks due to the absence of significant anthropopression hazards.

The statistic of the distribution of risk classes on the map is presented in Table 17 and Table 18.

Table 17. Distribution of risk classes within the whole PL-UA study area

GW risk index	Percent of the area, %
0,0 - 0,5 No risk	48,19
0,51 - 1,0 Very low	41,93
1,1 - 1,5 Low	2,5
1,51 - 2,0 Average	3,67
2,1 - 2,5 High	2,23
2,51 - 3,9 Very high	1,48

Table 18. Distribution of risk classes on the territory of PL-UA study area

Poland (area=8008 km^2)		**Ukraine (area=19016 km^2)**	
GW risk index	percent of the area, %	GW risk index	percent of the area, %
0,0 - 0,5 No risk	46,33	0,0 - 0,5 No risk	48,97
0,51 - 1,0 Very low	52,3	0,51 - 1,0 Very low	37,56
1,1 - 1,5 Low	0,59	1,1 - 1,5 Low	3,31
1,51 - 2,0 Average	0,17	1,51 - 2,0 Average	5,15
2,1 - 2,5 High	0,09	2,1 - 2,5 High	3,13
2,51 - 3,9 Very high	0,52	2,51 - 3,9 Very high	1,88

The distribution of risk classes of the studied territory by catchment basins is given in Table 19, Table 20 and Table 21.

Table 19. GW risk in the Bug catchment by classes (S=15580 km^2)

Poland (area=5129 km^2)		**Ukraine (area=10451 km^2)**	
GW risk index	percent of the area, %	GW risk index	percent of the area, %
0,0 - 0,5 No risk	32,4	0,0 - 0,5 No risk	52,93
0,51 - 1,0 Very low	66,06	0,51 - 1,0 Very low	39,8
1,1 - 1,5 Low	0,53	1,1 - 1,5 Low	2,34
1,51 - 2,0 Average	0,08	1,51 - 2,0 Average	1,81
2,1 - 2,5 High	0,12	2,1 - 2,5 High	2,67
2,51 - 3,9 Very high	0,82	2,51 - 3,9 Very high	0,45

Table 20. GW risk in the San catchment by classes (S=4556 km2)

Poland (area=2225 km^2)		Ukraine (area=2331 km^2)	
GW risk index	percent of the area, %	GW risk index	percent of the area, %
0,0 - 0,5 No risk	66,16	0,0 - 0,5 No risk	42,47
0,51 - 1,0 Very low	32,72	0,51 - 1,0 Very low	42,81
1,1 - 1,5 Low	0,63	1,1 - 1,5 Low	3,56
1,51 - 2,0 Average	0,45	1,51 - 2,0 Average	9,78
2,1 - 2,5 High	0,04	2,1 - 2,5 High	0,39
2,51 - 3,9 Very high	0	2,51 - 3,9 Very high	0,99

Table 21. GW risk in the Dniester catchment by classes (S=6014 km2)

Poland (area=251 km^2)		Ukraine (area=5763 km^2)	
GW risk index	percent of the area, %	GW risk index	percent of the area, %
0,0 - 0,5 No risk	71,71	0,0 - 0,5 No risk	40,79
0,51 - 1,0 Very low	27,89	0,51 - 1,0 Very low	34,13
1,1 - 1,5 Low	0,4	1,1 - 1,5 Low	5,19
1,51 - 2,0 Average	0	1,51 - 2,0 Average	9,65
2,1 - 2,5 High	0	2,1 - 2,5 High	5,24
2,51 - 3,9 Very high	0	2,51 - 3,9 Very high	5

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Part 3. Assessment of cross-border anthropogenic pressure on groundwater state in the Latvian-Estonian pilot area.

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Introduction

Article 5 of the Water Framework Directive requires identification of significant pressures to cause groundwater to be in less than a good chemical and/or quantitative status, as well as the impact assessment of the identified pressures. The identification of significant pressures and their resulting impacts (which in turn could lead to a reduced groundwater chemical and/or quantitative status) can involve different approaches: field surveys, inventories, numerical tools (e.g. modeling), expert judgment or a combination of approaches.

To identify and assess the impact of anthropogenic pressure on the groundwater state in the Estonian-Latvian transboundary area, initially Guidance Document No.3 "Analysis of Pressures and Impacts" was studied to understand what pressures should be assessed according to the Water Framework Directive and what are the most commonly used methods for assessment of the pressures to find the most suitable solution for the Estonian-Latvian transboundary area (**Chapter 1** - *General approach for the analysis of pressures and impacts*).

After identifying the most important groups of anthropogenic pressures sources in the Estonian-Latvian transboundary area (point and diffuse source pollution, as well as groundwater abstraction), data on these types of pressures were collected from the reports previously prepared within the EU-WATERRES project, as well as the information was supplemented and updated using information from the national databases as well as other sources of information (**Chapter 2** - *Anthropogenic pressures on the Estonian-Latvian transboundary area*).

Since one of the main elements in assessing the impact of pressures on groundwater is their vulnerability to pollution, before assessing the impact of the identified pressures, multiple vulnerability maps were developed for the Estonian-Latvian transboundary area - both for the Quaternary and most useful aquifer layers, finding the most appropriate methods for the Estonian-Latvian transboundary area and making appropriate modifications to the methods (**Chapter 3** - *Groundwater vulnerability to pollution and depletion*).

As the last step, the assessment of the impact of the identified pressures on groundwater in the Estonian-Latvian transboundary are was carried out: in the case of diffuse pressure, applying modified version of the DRASTIC method, in the case of point source pressure - by performing particle-tracking simulation using MODPATH, and in the case of groundwater abstraction pressure - using regional-scale hydrogeological model, previously developed during the EU-WATERRES project specifically to assess the water level changes of the groundwater aquifers (**Chapter 4** - *Assessment of the transboundary pressures on groundwater*). The main conclusions were summarized in **Chapter 5**.

1. General approach for the analysis of pressures and impacts

1.1. Prerequisites for the analysis of pressures and impacts

The Water Framework Directive (WFD) is a comprehensive legislative framework established by the EU that aims to protect and improve the quality of all water resources, including inland surface waters, transitional waters, coastal waters, and groundwater. Its primary objective is to prevent further deterioration of water resources and promote their sustainable management to achieve good water status.

The WFD seeks to enhance the protection and improvement of the aquatic environment through specific measures. These measures include the progressive reduction of discharges, emissions, and losses of priority substances, as well as the cessation or phasing-out of discharges, emissions, and losses of priority hazardous substances. By implementing these measures, the WFD aims to prevent pollution and promote the sustainable use of water resources based on long-term protection. The WFD also addresses the issue of groundwater pollution. It ensures the progressive reduction of pollution of groundwater and takes measures to prevent further contamination, recognizing the importance of safeguarding this vital water source. Furthermore, the WFD acknowledges the significance of mitigating the effects of floods and droughts. By implementing appropriate strategies and measures, the directive contributes to reducing the risks associated with extreme weather events and supports efforts to manage water resources more effectively during periods of excessive rainfall or prolonged drought.

According to the WFD, **EU member states have key responsibilities to fulfill**. Firstly, they need to identify and delineate the individual river basins within their territories. This step is crucial as it allows for a more focused and localized approach to water management. Once the river basins are identified, member states are required to characterize these river basin districts in terms of the various pressures, impacts, and economics of water uses within their respective territories. This involves understanding the sources of pollution, the impact of human activities, and the economic aspects of water utilization. Furthermore, the WFD mandates the establishment of an operational monitoring network by member states. This network aims to gather reliable and consistent data on the status of water bodies within the river basin districts. Monitoring provides vital information on the ecological, chemical, and quantitative aspects of water resources, helping to assess their overall health and identify areas that require intervention. Based on the data collected through monitoring and a thorough analysis of the characteristics of the river basin districts, member states are required to identify a program of measures. These measures should be designed to effectively achieve the environmental objectives of the WFD while taking into consideration the costs involved. The goal is to develop a cost-effective plan that addresses the specific challenges and needs of each river basin district. Member states are expected to implement and operationalize the measures outlined in their programs by a specified deadline. The initial target for implementation was set for 2015, but it can be extended to 2027 or later if constrained by natural conditions. This flexibility allows for realistic timelines, considering the complexity of implementing measures across diverse river basins and the need to account for any unforeseen challenges.

The impact assessment should include information from groundwater characterization and review process as these are crucial aspects of the Water Framework Directive's (WFD) implementation. The review process of the analysis of pressures and impacts on groundwater involves the following steps to ensure a comprehensive understanding of groundwater resources and the identification of potential risks:

1. Initial characterization, including identification of pressures and risk of failing to achieve objectives. The characterization provides an overview of the existing conditions and potential challenges faced by groundwater bodies;
2. Further characterization for at risk groundwater bodies. This step investigates deeper into understanding the specific characteristics and vulnerabilities of these groundwater bodies, allowing for more targeted measures to address their particular challenges;
3. Review of the impact of human activity on groundwaters for transboundary and at risk groundwater bodies. It is important to examine the influence of human actions, such as agriculture, industry, or urban development, on the quality and quantity of groundwater resources. Understanding these impacts helps in developing appropriate management strategies and measures;
4. Review of the impact of changes in groundwater levels for groundwater bodies for which lower objectives are to be set. This step analyzes the effects of natural or anthropogenic factors on groundwater levels, which can have implications for the ecological status and functioning of these bodies;
5. Review of the impact of pollution on groundwater quality for which lower objectives are to be set. This activity focuses on assessing the presence of pollutants, their sources, and their potential effects on the groundwater quality, ensuring that appropriate measures are taken to address and mitigate pollution.

By following these five steps in the review process, authorities and stakeholders gain insights into the pressures and impacts on groundwater resources. This knowledge forms the basis for developing effective management strategies and measures to achieve the objectives set by the Water Framework Directive and safeguard the quality and sustainability of groundwater bodies.

1.2. General approach for the analysis of pressures and impacts

The general approach for the analysis of pressures and impacts, as outlined by the Water Framework Directive (WFD), involves several key stages to comprehensively assess the state of water bodies. These stages are pictured in the Figure 1 and can be generally listed as following:

1. Identifying driving forces and pressures: This stage involves identifying the various factors and activities, both natural and human-induced, that can potentially drive changes and exert pressures on water bodies;
2. Identifying the significant pressures: Significant pressures having the most substantial influence on the water bodies must be determined with an impact capable of potentially causing the failure for the water body to have a good status.
3. Assessing the impacts: Assessment of the impacts caused by the identified pressures on the status of water bodies. This involves analyzing the direct and indirect effects on the physical, chemical, and biological components of the water system. The assessment considers the short-term and long-term consequences of the impacts and their potential implications for the achievement of the environmental objectives.
4. Evaluating the likelihood of failing to meet the objectives: Evaluation of the likelihood of not achieving the objectives set by the WFD due to the identified pressures and impacts. It includes considering the current status, trends, and future projections of the water bodies' ecological condition in light of the assessed impacts. This evaluation helps in identifying areas where

additional measures or interventions may be necessary to ensure the attainment of the environmental objectives.

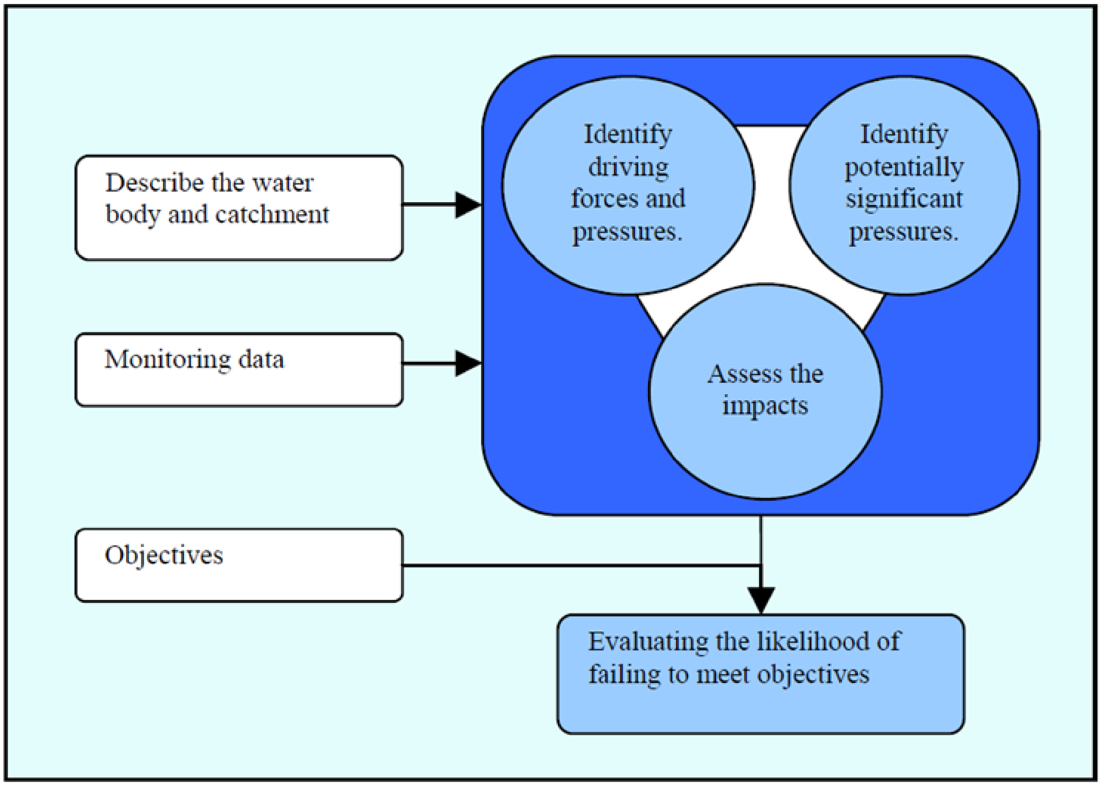


Figure 21. Key components in the analysis of pressures and impacts (IMPRESS, 2003)

The description of a water body and its catchment area serves as the foundation for the analysis of pressures and impacts. This description should include various types of information such as climate, geology, soil, and land use, which contribute to understanding the context and potential influences on the water body. Throughout the analysis process, relevant monitoring data specific to the water body in question may be introduced. Monitoring data can also be compared with driving forces to identify areas where pressures are likely to lead to a failure in meeting the objectives set by the WFD.

1.3. Identification and assessment of driving forces and pressures

In order to comprehensively analyze the pressures on water bodies, it is crucial to identify the driving forces that may contribute to these pressures. The developed description of water body and delineated catchment is crucial to assess any possible driving force and pressure that might pose any negative impact on it. Various types of possible driving forces can exert pressure on water bodies (Figure 2) can be broadly categorized as following:

- Diffuse source pollution: includes agriculture, forestry, urban drainage, and other non-point sources. These sources contribute to the overall pollution load, with contaminants entering water bodies through runoff and leaching processes.

- Point source pollution: wastewater discharges, industrial activities, mining operations, contaminated land, etc. These sources release pollutants directly into water bodies, resulting in localized impacts.
- Abstraction: leads to a reduction in water availability and flow in rivers;
- Artificial recharge: can influence water bodies by replenishing groundwater resources.

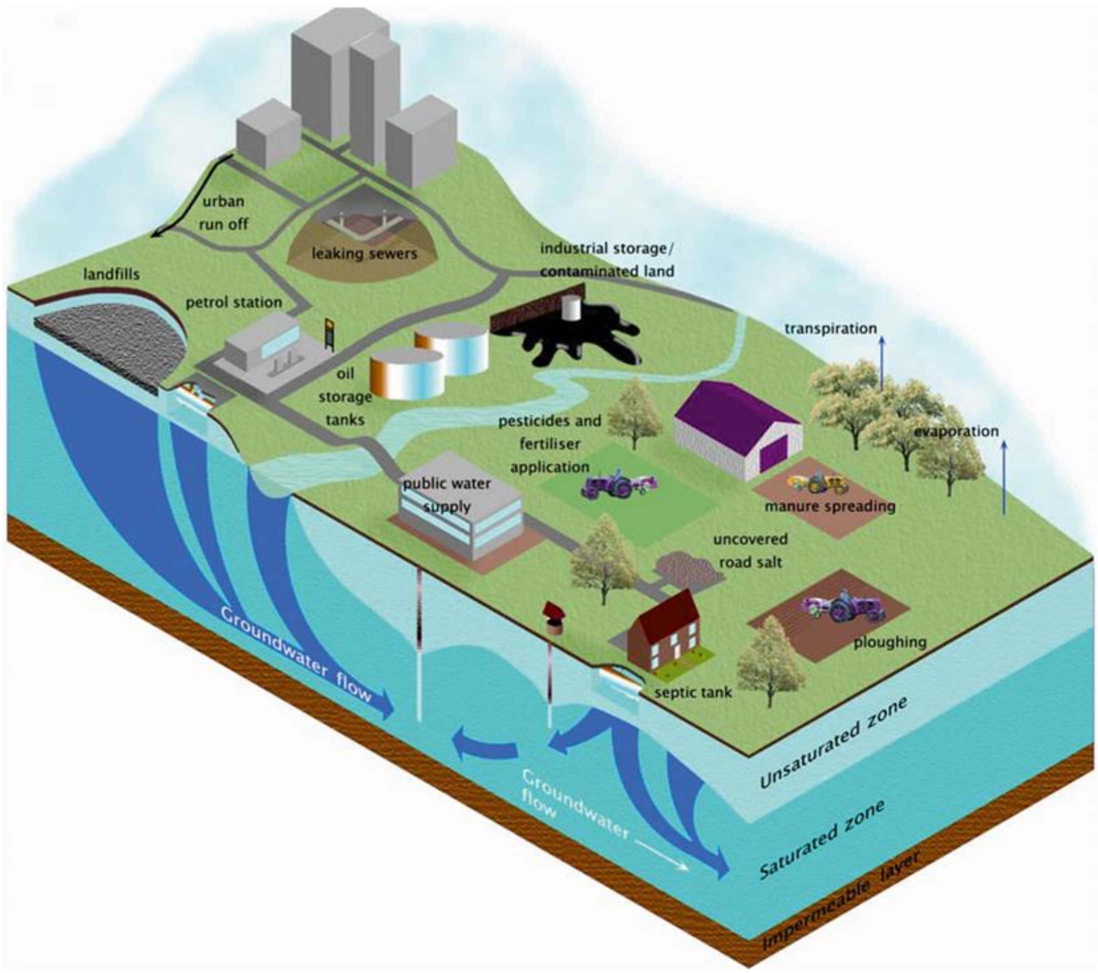


Figure 22. Schematic representation of potential pressures (UK Groundwater Forum, n.d.)

When compiling the inventory of pressures, it is anticipated that numerous pressures identified may have little or no actual impact on the water body. For the surface waters, WFD only necessitates the **identification of significant pressures**, which are interpreted in this guidance as pressures that contribute to an impact capable of potentially causing the failure of an objective. In the case of groundwaters, the initial characterization entails conducting a general analysis of pressures. However, this analysis is conducted within the context of assessing the risk of failing to achieve the objectives.

1.4. Pollution pressures

Pollution pressure is a potential impact on water bodies resulting from activities that can directly or indirectly lead to deterioration in their ecological or chemical status. Pollution pressure primarily arises from human activities that can introduce various pollutants, including chemicals, nutrients, sediments, pathogens, and toxic substances, into water bodies, including groundwater. Diffuse and point-source pollution are two primary categories of pollution that can significantly impact water bodies, including groundwater resources.

Diffuse pollution refers to the widespread and dispersed release of pollutants over a broad area, often originating from various non-point sources. These pollutants can infiltrate the soil and gradually leach into groundwater, posing a long-term threat to its quality (see Table 1). Diffuse pollution, due to its dispersed nature, can lead to a gradual accumulation of contaminants, compromising the overall quality of groundwater resources over time.

Table 22. Examples of diffuse source pressures and their impacts (modified from IMPRESS, 2003)

Activity or Driving force	Pathway causing Pressure	Possible change in state or impact
Agriculture	Nutrient loss from agriculture by: • surface runoff • soil erosion • artificial drainage flow • leaching (*i.e.* interflow, spring water and groundwater) (includes excess fertilisers and manures and mineralization of residues)	Nutrients modify ecosystem
	Pesticide loss by pathways mentioned above	Toxicity, contamination of potable water supplies
Industry discharges to the atmosphere	Deposition of compounds of nitrogen and sulphur.	Acidification of surface and groundwater bodies. Eutrophication
Transportation	Pollutant spillages	Gross pollution of water bodies
	Use of salt as de-icer	Elevated chloride concentration
	Engine exhausts	Increase in acidifying chemicals in atmosphere and hence deposition

Point-source pollution involves pollutants discharged from specific and identifiable sources that release pollutants directly into the water body or groundwater, potentially causing localized contamination and immediate deterioration of water quality. Contaminants released from these sources can quickly reach groundwater, causing rapid contamination of specific areas. Examples of point source pollution pressures and their impacts are summarized in Table 2.

Table 23. Examples of point source pressures and their impacts (modified from IMPRESS, 2003)

Activity or Driving force	Pressure	Possible change in state or impact
Industrial	Effluent disposal to surface and groundwaters	Toxic substances have direct effect, increased suspended solids, organic matter alters oxygen regime, nutrients modify ecosystem
Urban activity	Effluent disposal to surface and groundwaters	As above
Landfill	Chemical fluxes in leachate	As above
Animal burial pits (e.g. following epidemic)	Contaminated leachate	As above
Former land use	Contaminated land	Various
Thermal power generation	Return of cooling waters cause alteration to thermal regime	Elevated temperatures, reduced dissolved oxygen, changes in biogeochemical process rates
Dredging	Sediment disposal	Smothering of bed, alteration of invertebrate assemblage
Fish farming	Feeding, medication, escaping	Nutrients, diseases, veterinary products, artificial fish population, modified food web

1.5. Quantitative resource pressures

In accordance with the Water Framework Directive (WFD), the concept of quantitative status is explicitly addressed only for groundwater bodies, while quantitative pressure evaluation must be assessed for all water bodies. Quantitative pressures hold significance across all water bodies as they influence crucial factors such as dilution, residence time, and storage. Table 3 provides illustrative examples of quantitative pressures.

Table 24. Example quantitative pressures and their impacts (modified from IMPRESS, 2003)

Activity or Driving force	Pressure	Possible change in state or impact
Agriculture and land use change	Modified water use by vegetation. Land sealing	Altered recharge of groundwater body
Abstraction for irrigation, public & private supply	Reduction in flow or aquifer storage	Reduced dilution of chemical fluxes. Reduced storage. Modified flow and ecological regimes. Saline intrusion. Modified dependent terrestrial ecosystem.
Managed aquifer recharge	Increased storage	Increased outflow. Contamination of groundwater.
Water transfer	Increased flow in receiving water	Modified thermal, flow and ecological regimes

1.6. Pressure assessment

Significance of a pressure on a water body must be evaluated using the knowledge of the pressures within the catchment area, combined with a conceptual understanding of water flow dynamics, chemical transfers occurring within the water body and its catchment system. It is crucial to have a knowledge that a link a pressure with its potential impact on water body based on the functioning of the catchment system/aquifer. One way to identify important pressures is by integrating this understanding with a comprehensive list of all pressures and considering the specific characteristics of the catchment and by applying specific tools (i.e. numerical models) to simulate impact of all pressures. A simpler approach is to use rules that indicate if a pressure is significant. This strategy involves assessing the magnitude of a pressure in relation to a criterion or threshold that is specific to the type of water body. However, it is crucial to acknowledge that applying a standardized set of thresholds throughout Europe would overlook the unique characteristics of each water body and its susceptibility to different pressures. For this task expert judgement can be effectively incorporated while being grounded in robust scientific principles.

1.7. Assessment of impacts

To evaluate the impacts on a water body, it is necessary to gather quantitative information/characterization that describes either the current state of the water body/system itself or the pressures that acts on it, but the specific analysis will depend on the availability of data. Similar to the identification of significant pressures discussed earlier, this assessment demands a conceptual understanding of the factors causing impacts. In many instances, a simple approach of this type may suffice for evaluating the impact of a pressure. However, relying solely on such simple approaches would not be always appropriate considering the diversity of catchments and water body types, interplaying pressures, conceptual models, data requirements, and potential impacts in real-world scenarios.

In certain cases, a pressure that appears straightforward in one system (i.e. in groundwater, surface water) can have a more complex impact pattern in other systems, such as ecosystems. This complexity calls for the adoption of advanced approaches to accurately assess and understand these impacts. However, the feasibility of employing sophisticated process-based numerical simulations may be limited by factors such as data scarcity or inadequate funding. Consequently, finding a balance becomes essential, whereby less resource-intensive methods are selected that align with the available data while still providing relevant result.

The concept of "potential impact" can be used and even suggested to describe the expected effects of a pressure on a groundwater body and its evaluation in terms of the risk of failing the objectives. For pollution pressures, the potential impact is assessed by considering the combination of pollution pressure at the ground surface and the vulnerability of the groundwater body to pollution. For example, a high pollution pressure above an aquifer may have little impact on the groundwater body if it is protected by a thick layer of low permeability overburden. In the case of quantitative pressures like abstraction, the potential impact involves lowering of water levels and outflows, which can be estimated using the conceptual model of the flow system and conducting a water balance for the groundwater body.

The assessment of potential impacts is typically carried out after refining the conceptual model. Based on the conceptual model, a determination is made regarding whether the groundwater body is likely to fail in achieving good chemical status and good quantitative status. When there are differences in the predicted status, the assessment considers the poorer outcome. To validate the assessments of potential impacts resulting from pressures, it is important to use monitoring data from areas where such data are available. These data not only help validate the assessments but also provide insights into any trends in water chemistry, further enhancing the understanding of the system and its potential risks.

1.8. Approaches to assess impacts

Observation data is crucial in assessing the impact on water bodies, particularly groundwater. Direct observations from the water body itself present an opportunity for a direct evaluation of the impact, but the diversity of impacts requires the utilization of various types of data. It is crucial to define an appropriate indicator that could accurately capture the expected impact. Apart from the data, it is also required to construct an appropriate indicator that accurately captures the expected impact, although many pressures do not lead to a definitive impact but rather alter the likelihood of adverse conditions occurring. Assessing water quality poses its own challenges as data quality, variability, seasonality and other aspects must be taken into account to perform correct statistical analysis.

Modelling approaches are useful in investigating pressures and impacts on groundwater, serving as valuable tools for estimating the potential effects. Modelling should be considered as subordinate or complementary to monitored data obtained directly from the water body. There are many reliable and straightforward modelling approaches available – these models can be designed to represent a single domain, such as a river, lake, transitional water, coastal water, or groundwater, or they can encompass multiple domains within a unified framework. These models have the capability to simulate various aspects of the flow, hydromorphology, recharge and hydrogeochemistry of the water body, either independently or in an integrated manner. The complexity of domain models can be significantly enhanced using more observation data or more features of conceptual understanding, however, it should be noted that a simple model is not inherently less accurate than a complex model and often simple models are more suitable. Nevertheless, the suitability of a modelling approach depends on the specific objectives and requirements of the groundwater investigation.

Monitoring data plays a crucial role in assessing the impacts on water bodies, including groundwater. In some cases, monitoring data may indicate the absence of current impacts. This information reveals that none of the initially identified pressures are significant or that the time required for a pressure to manifest as an impact has not yet elapsed. This aspect is particularly relevant for groundwater where pollutants travel slowly. Monitoring data can also serve as a validation tool for models, ensuring that the inputs and processes accurately replicate the observed data. However, it is important to note that even if the observed data for a specific water body does not show any impacts, there might still be a causal relationship with impacts on other water bodies within the same river basin district. Conversely, when observed data indicates the presence of an impact, understanding the nature of the impact becomes essential for conducting a thorough pressures and impacts analysis. Traditionally, impacts have been quantified based on chemical or physico-chemical parameters exceeding predetermined thresholds. This can be effectively addressed by employing a simple conceptual model that incorporates known activities and associated pressures, facilitating a straightforward assessment of the situation.

1.9. Conceptual model as an approach

Conceptual understanding of the flow system, chemical variations, and ecological dynamics within water bodies is essential to effectively characterize groundwater and understand its interactions with surface ecosystems. The advantage of the conceptual understating is that it integrates diverse data types such as physical, biological, and chemical information into a comprehensive understanding of the system. As new data becomes available, it contributes to the refinement or modification of the conceptual model, while the model itself may identify errors or limitations in the data. The early stages of groundwater characterization involve constructing basic conceptual models of groundwater flow, chemical processes and interactions. This includes delineating the boundaries of groundwater bodies, gaining initial insights into the flow and geochemical systems, and assessing their interaction with surface water bodies and terrestrial ecosystems. It also includes examining water quality information and evaluating the pressures on the system. From the early stages of groundwater body delineation, it is crucial to develop a coherent understanding of the aquifer system's quantity, quality, and the potential consequences of pressures. Throughout the characterization process, all collected data related to the groundwater body's characteristics should be tested against the conceptual model to refine the model and identify any data inconsistencies.

2. Anthropogenic pressures on the Estonian-Latvian TBA

The WFD requires the identification of significant pressures from point sources of pollution, diffuse sources of pollution, modifications of flow regimes through abstractions or regulation and morphological alterations, as well as any other pressures.

According to WFD Annex 2, it is necessary to assess the following groundwater pressures:

- point sources of pollution;
- diffuse sources of pollution;
- abstraction;
- artificial recharge.

For the identification of the anthropogenic pressure on the groundwater of the Latvian-Estonian pilot territory, the Guidance document No.3 "Analysis of Pressures and impacts" were used as a basis, which describe in more detail the analysis of pressures and impacts, in order to achieve the goals of the WFD.

2.1. Point source pollution

In accordance with the requirements of the Water Framework Directive (2000/60/EC), it is important to identify significant point pressure sources for the initial characterization of groundwater. Guideline document No.3 "Analysis of Pressures and impacts" specifies the types of point pressure types that should be considered in the assessment of anthropogenic pressure of groundwater.

Guidance document mentions that the following point-source pressures should be evaluated for groundwater assessment:

- waste water;
- industry;
- mining;
- contaminated land;
- agriculture point;
- waste management;
- aquaculture.

In order to identify significant point pressures in the Latvian-Estonian transboundary area, information was collected from the national registers and databases of both countries:

- register of contaminated and potentially contaminated sites (LV);
- State Environmental Service register of category A polluting activity permits (LV);
- database of shallow groundwater pollution of petrol stations and oil bases (LV);
- data from the Agricultural Data Center on the number of animals (LV);
- Estonian Information system of Environmental permits (EE);
- database on contaminated and abandoned sites (EE);
- The European Pollutant Release and Transfer Register.

Considering the compiled information from the aforementioned registers, the proposed types of point-pressure sources (according to guidelines) were evaluated in the Latvian-Estonian pilot territory.

Wastewater. Evaluating the data of the two countries on point pressures, it was assumed that wastewater does not cause a significant pressure on groundwater, as urban wastewater treatment facilities have been modernized and reconstructed in recent years. Data on private household wastewater is not available.

Industrial. This is the most common type of point-pressure source in the study area. Several petrol stations, two asphalt concrete factories, a bitumen factory, two livestock complexes and a heating station were identified as potentially significant sites.

Contaminated land. On the Estonian side, there are two former military sites - Vilaski rocket installation area and nuclear warhead warehouse, as well as Vilaski rocket base town and car base.

Agriculture point. In the pilot area, two storage places for agricultural fertilizers have been identified, as well as one agricultural fuel storage place.

Waste management. On the Latvian side, there is also one working landfill (Daibe) near the city of Valmiera. The landfill is managed and maintained in compliance with all environmental protection requirements. Environmental quality monitoring is regularly carried out in the territory. So far, no contamination has been detected in groundwater. The landfill has been issued a category A polluting activity permit.

Mining. There is one active dolomite mining quarry (Ape) in the study area. It is an active open-pit dolomite quarry. Groundwater level lowering is performed for mining purposes, so a significant pressure of groundwater abstraction has also been identified in this quarry. Therefore, this area is described more in the subchapter of identification of the significant water abstraction.

Aquaculture. Aquaculture facilities are not common in the pilot area.

In general, significant point-pressure sites were identified within the framework of the Work package No.2 report "Integrated groundwater observation network between neighboring countries for 2 transboundary aquifers". In total, 17 point-pressure sites were identified in the pilot area, of which 8 are located on the Latvian side, and 9 on the Estonian side. As part of this report, the list was revised, as a result, it was supplemented with 1 polluted place in the territory of Latvia, in the city of Valka (see Figure 3).

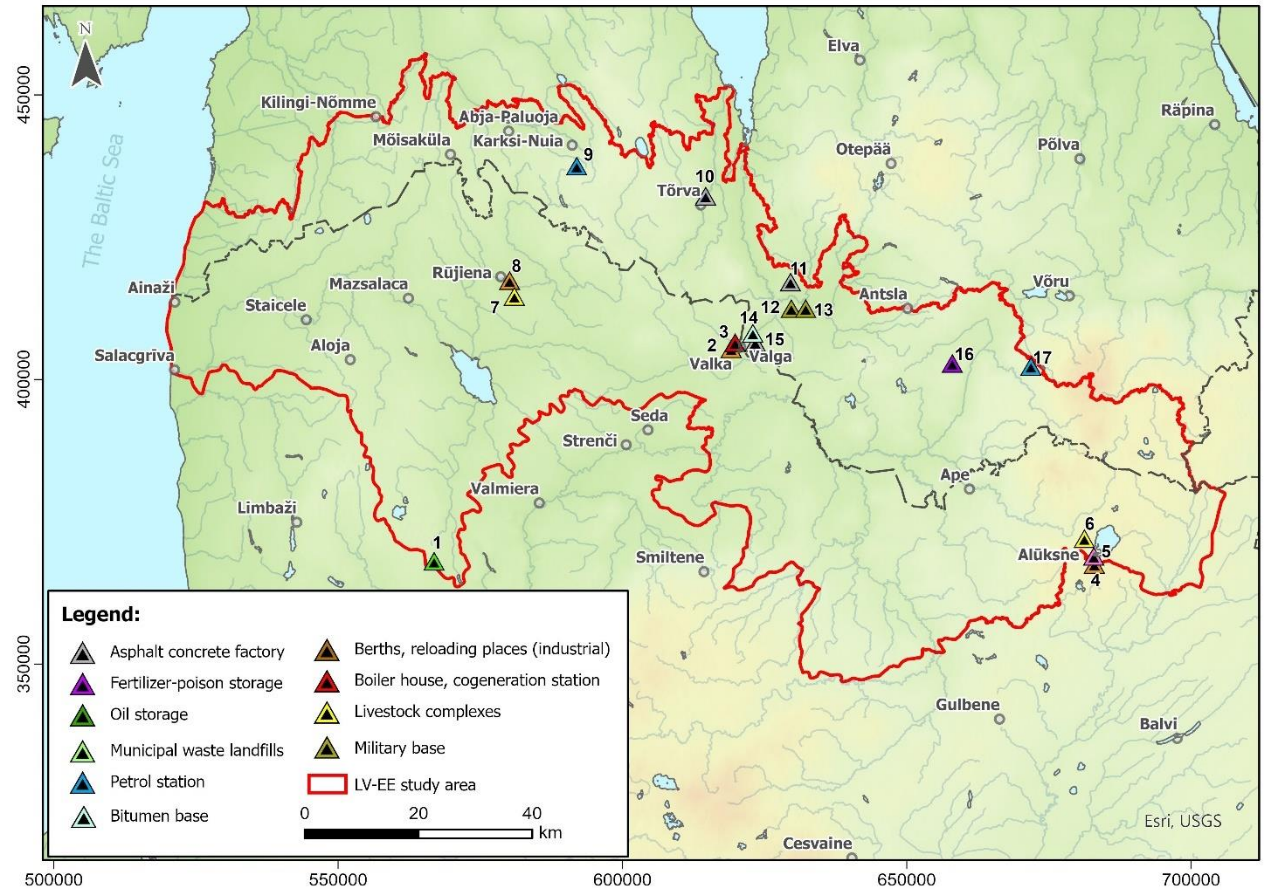


Figure 23. Identified point-source pressure sites in Latvian-Estonian study area

Figure 3 shows that significant point-pressure sites are located mainly near large settlements. So, for example, the most places 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 countries, so it is necessary to pay more attention to this place in the context of cross-border impact assessment.

All identified significant point-pressure sites in the Latvian-Estonian pilot area are described in Table 4.

Table 25 Description of identified point-source pressure sites

No	Name	Category (Guidance doc. No.3)	Type	Description	Status	Pollutants
1.	Solid waste landfill "Daibe"	Waste management	Municipal waste landfills	The landfill "Daibe" was established in 2004. Waste processing and storage is carried out in it. The landfill is established and managed in compliance with environmental requirements and regulatory enactments. In the current situation, there is no threat to the quality of GW.	Not polluted	-
2.	"Tīne" LLC gas station and oil base	Industry	Petrol station	The area of the oil base is around 4.5 ha. The main activity of the oil base is the pumping and storage of oil products - gasoline and diesel fuel. A monitoring network of 3 observation wells has been created to monitor groundwater quality. The place is included in the list of potentially polluted places, because historical contamination with oil products has been found in the groundwater	Polluted	Petroleum products
3.	Pollution on Rujiena street 5, Valka	Industry	Boiler house, cogeneration station	The former boiler house of the Valka city heating network is located in the territory. In autumn 2022, GW samples were taken from 4 wells, the content of oil products and volatile hydrocarbons was determined in all groundwater samples. Contaminated groundwater is located in the depth of ~2.3 m to 4.0 m (from land surface).	Polluted	Petroleum products and polycyclic aromatic hydrocarbons
4.	State JSC "LATVIJAS AUTOCEĻU UZTURĒTĀJS" gas station	Industry	Petrol station	In 2005, a monitoring network with 3 wells was installed in the territory. Significant contamination of soil and groundwater with oil products (fuel) was detected in the territory. Excess oil products were found in the soil sample. Also, the content of oil products in groundwater samples exceeds the limit value - 0.2 mg/l (well No.1 - 1.46 mg/l and well No.3 - 7.03 mg/l).	Polluted	Petroleum products
5.	SW bay of Aluksne lake	Industry/contaminated land	Berths, reloading places (industrial)	Historical pollution in the sediments of the SW part of Lake Alūksne. The State Electrotechnical Factory and the city heating house were located near the lake. The results of the analysis carried out in 2016 show different types of impacts, however, the exceedance of the limit values was caused by the historical anthropogenic impact from the city of Alūksne - basically from the historical industrial activity (wastewater of the factory, fuel oil heating house, etc.) and farms on the shore of the lake.	Polluted	Petroleum products, heavy metals

No	Name	Category (Guidance doc. No.3)	Type	Description	Status	Pollutants
6.	"Alūksnes putnu fabrika" LLC ("VISTAKO" LLC), poultry farm	Industry	Livestock complexes	The factory has been engaged in the production of chicken eggs since 1961 and it is the second largest production facility of this type in Latvia. The company implements a zero-waste production policy, thus reducing the potential impact on the environment. The factory has been issued a category A polluting activity permit.	Not polluted	-
7.	"KUNTURI" LLC, pig farm	Industry	Livestock complexes	The pig production plant started its operation in 1993. The company is engaged in pig breeding, as well as the production of meat products. The factory has been issued a category A polluting activity permit.	Not polluted	-
8.	"EAST-WEST TRANSIT" LLC gas station "RŪJIENA"	Industry	Petrol station	In 1999, geological survey works were carried out in the territory - a monitoring network was established. In 2005, additional observation wells were installed and soil quality determination works were carried out. No excesses of oil products were found in the analyzes of the soil samples. Excesses of oil products were found in the groundwater samples, which indicates severe pollution: 13.1 mg/l (allowable value - 0.2 mg/l).	Polluted	Petroleum products
9.	Äriküla fertilizer-poison storage	Agricultural point	Fertilizer-poison storage	The former fertilizer-poison storage is located in a residential area. It belongs to third category of pollution points: open or emergency prone storage facilities that had a significant risk of locally polluting soil, groundwater or surface water	Pollution mostly eliminated	-
10.	Härma asphalt concrete factory	Industry	Asphalt concrete factory	The former asphalt concrete factory is located in an industrial and residential zone. Groundwater may be contaminated. The surface is polluted by visual assessment.	Not polluted	Petroleum products, shale oil
11.	Tsirguliina asphalt concrete factory	Industry	Asphalt concrete factory	The former asphalt concrete factory is located in an industrial zone. Pollution consists of petroleum products that have spilled onto the ground. Belongs to the fourth category - residual pollution objects, where there is a risk of soil or surface water pollution.	Pollution mostly eliminated	Petroleum products, shale oil
12.	Vilaski rocket base town and car base	Contaminated land	Industrial objects	The former base of strategic medium-range missiles in Vilaski had underground vaults and a control center with a total of 2 floors underground. Currently, a few buildings in the town have been repaired and are in use, the rest of the buildings are falling apart.	Pollution mostly eliminated	Chemicals, petroleum products

No	Name	Category (Guidance doc. No.3)	Type	Description	Status	Pollutants
13.	Vilaski rocket installation area and nuclear warhead warehouse	Contaminated land	Industrial objects	Currently, the former launch complex has been demolished, two launch shafts have been filled with soil. The rocket storage facility is used as a storage facility. Belongs to the first category - residual pollution objects posing a direct threat to people	Pollution mostly eliminated	Aviation fuel, Petroleum products
14.	Valga bitumen base	Industry	Industrial object	The former bitumen base is located in an industrial zone. It is difficult to find a person who remembers and describes the activities of the former base, therefore the survey of the land should be done over the entire territory.	Polluted	Fuel oil
15.	Priimetsa asphalt concrete factory	Industry	Asphalt concrete factory	The Priimetsa asphalt concrete factory bitumen base was operational in 1956 until 1992. Soil and groundwater are polluted. Belongs to second category: residual pollution objects that pollute groundwater or surface water bodies and individual consumers' water intakes.	Pollution mostly eliminated	Phenols, Petroleum products, Polycyclic aromatic hydrocarbons
16.	Tsooru collective farm oil storage	Agricultural point	Oil storage	The former Tsooru collective farm oil storage belongs to category three: residual pollution objects, where there were open or emergency prone storages, which had a significant risk of local pollution of soil, groundwater or surface water	Polluted	-
17.	Rőuge toxic chemical warehouse	Agricultural point	Fertilizer-poison storage	The former Rőuge toxic chemical warehouse is located in the residential zone. Belongs to the fourth category: residual pollution objects, where there is a risk of soil or surface water pollution	Pollution mostly eliminated	Agricultural poisons, Fertilizers

The assessment of the impact of the significant point-pressure sites identified in the Latvian-Estonian pilot area is carried out in Chapter 4.2.

2.2. Diffuse source pollution

The proportion of land use types in the studied area can indirectly indicate the intensity of diffuse groundwater pollution, as well as the main causes of pollution and sources of pollutant emission. According to Corine Land Cover data the Estonian-Latvian transboundary area is mainly occupied by natural territories (forests and natural grassland areas, wetlands and water bodies), which in total make up 67% of the total area of the territory and cannot show significant adverse effects on the quality of groundwater (Figure 4, Table 5).

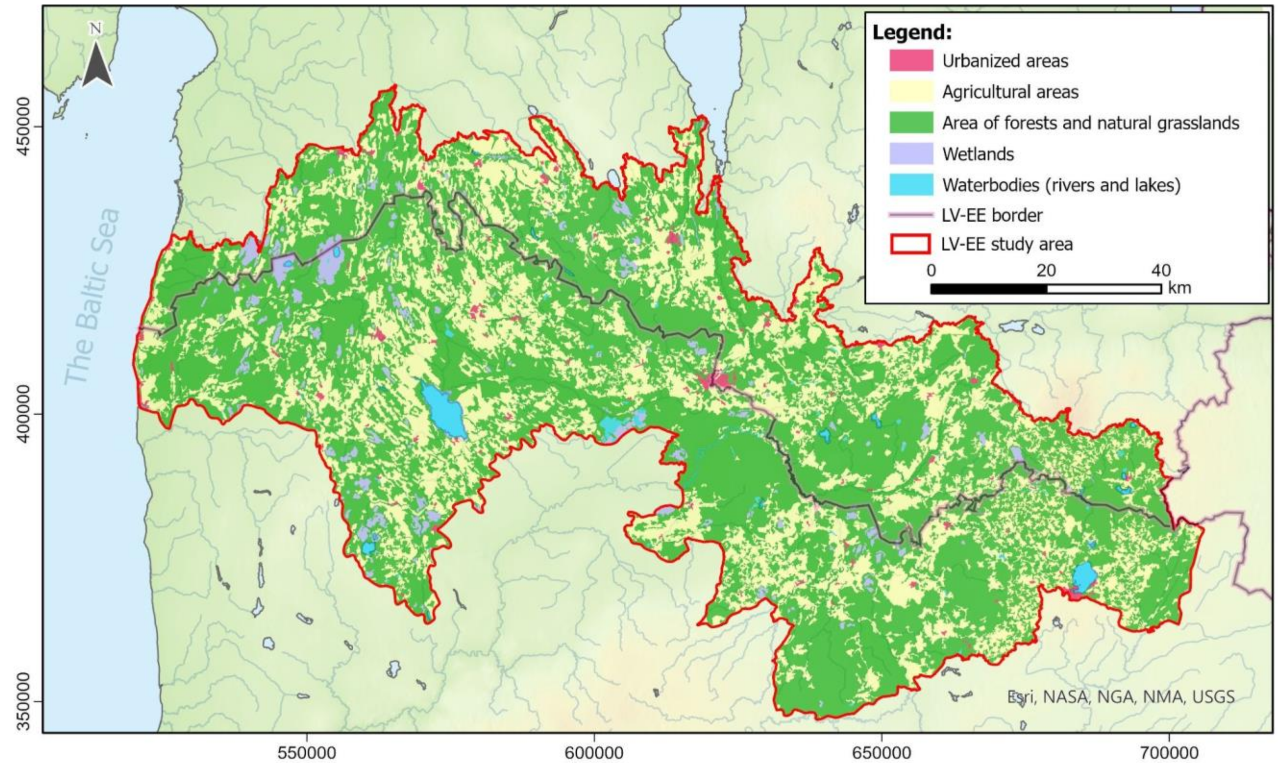


Figure 24. Land use types in the Estonian-Latvian transboundary pilot area (Corine Land Cover, 2018)

On the other hand, 33% of the transboundary area is occupied by urbanized and agricultural areas, which may be anthropogenically affected and can cause anthropogenic groundwater pollution (Figure 4, Table 5). 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).

Table 26. Land use types in the Estonian-Latvian transboundary pilot area

Land use	Types	Classes	Area, ha	Area, %
Urbanized areas (1.0%)	Urban fabric	Discontinuos fabric	6647	0.703
	Industrial, commercial and transports units	Industrial or commercial units	1283	0.136
		Road and rail networks and associated land	117	0.012

Land use	Types	Classes	Area, ha	Area, %
		Port area	31	0.003
	Mine, dump and construction sites	Mineral extraction sites	276	0.029
		Dump sites	26	0.003
	Artificial, non-agricultural vegetated areas	Green urban areas	397	0.042
		Sport and leisure facilities	385	0.041
Agricultural areas (32.3%)	Arable land	Non-irrigated arable land	146333	15.472
	Permanents crops	Fruit trees and berry plantations	359	0.038
	Pastures	Pastures	61837	6.538
	Heterogeneous agricultural areas	Complex cultivation patterns	43853	4.637
		Land principally occupied by agriculture	53568	5.664
Area of forests and natural grasslands (62.9%)	Forests	Broad-leaved forest	59876	6.331
		Coniferous forest	181395	19.179
		Mixed forest	198382	20.975
	Shrub and/or herbaceous vegetation associations	Natural grassland	4692	0.496
		Transitional woodland shrub	150755	15.939
	Open spaces with little or no vegetation	Beaches, dunes and sand plains	54	0.006
Wetlands (2.6%)	Inland wetlands	Inland marshes	2273	0.240
		Peat bogs	22192	2.346
Water bodies (rivers and lakes) (1.2%)	Inland waters	Water courses	476	0.050
		Water bodies	10536	1.114
	Marine waters	Sea an ocean	62	0.007
Total			**945807**	**100.000**

Figure 5 shows the distribution of agricultural pressure by group, of which non-irrigated arable land occupies the largest area (15.5%), while the smallest area is occupied by fruit trees and berry plantations (0.04%). Accordingly, other groups (complex cultivation patterns, land principally occupied by agriculture and pastures) occupy 43853-61837 ha, or about 4.6-6.5% of the total area of the transboundary area.

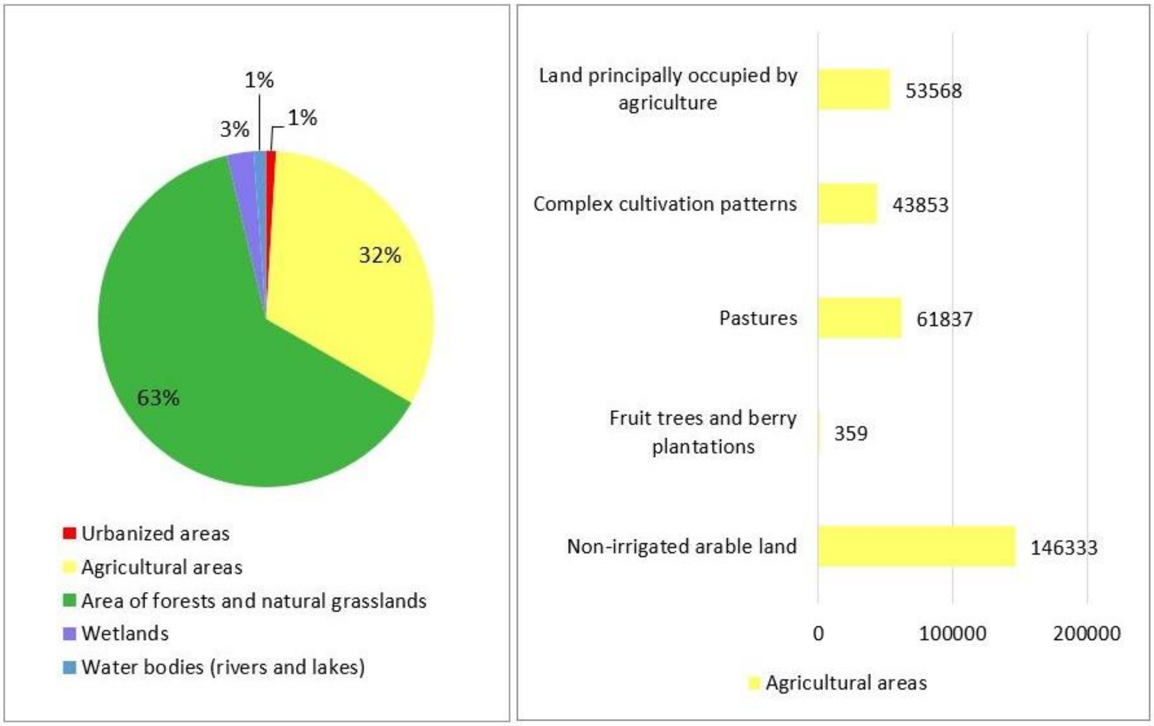


Figure 25.The distribution of agricultural pressure by group

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. Unfortunately, the information used is preliminary, because the data set does not separate intensively and less intensively used agricultural land and there is no actual data on the current load of agrochemicals (no data on the amounts of fertilizer use are available). Table 6 summarizes the actual data available in each country that could be used to estimate agricultural diffuse loads.

Table 27.The actual data about agricultural pressure

Latvia	Estonia
• Rural support service - areas of arable land, areas of territories used in agriculture (2018) • Agricultural Data Center - Farm Animals (2018)	• Map of agricultural parcels – Agricultural Registers and Information Board

In 2020, the European Environment Agency conducted a study on concentrations of nitrogen and phosphorus in European agricultural soils, as a result, different types of layers are prepared based on the fertilization data of 2010. One of the layers indicates nitrogen leaching to groundwater for the year 2010 (see Figure 6), which indicates that the agricultural pressure is more intense on the Estonian side and that larger amounts of nitrogen leaching into groundwater (shallow groundwaters) have been noted in the area under review.

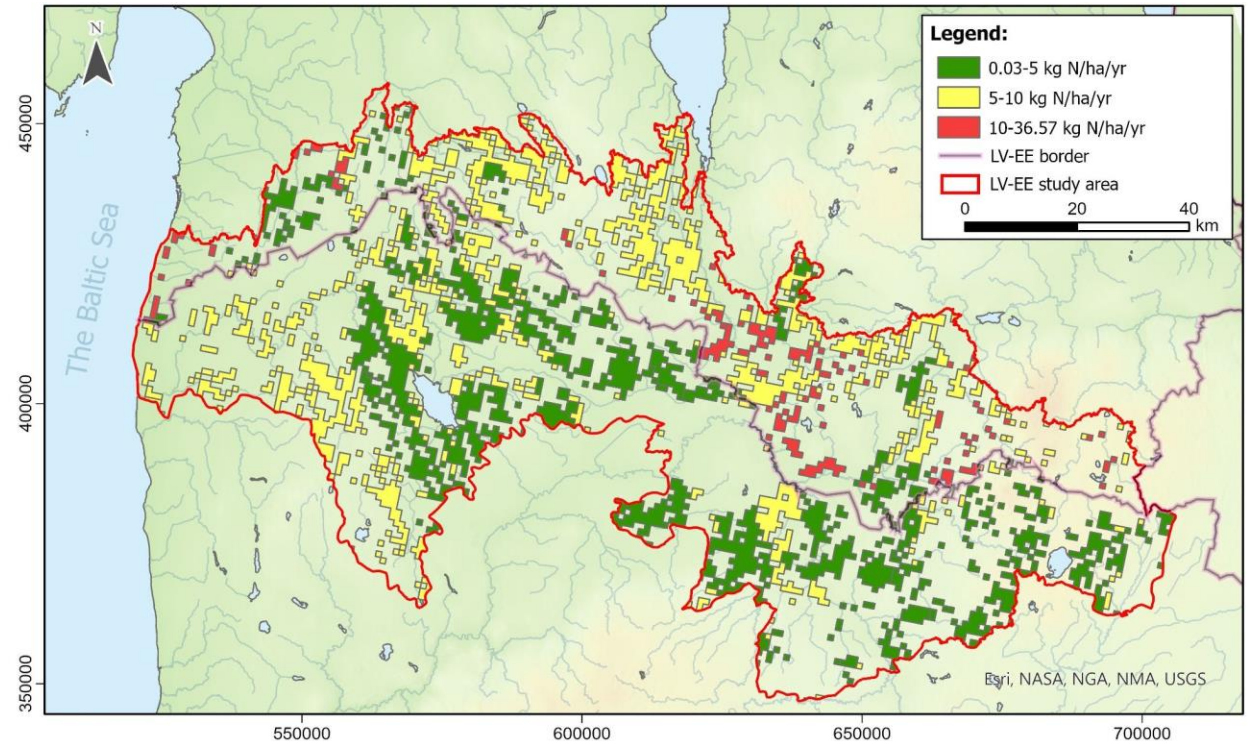


Figure 26. Nitrogen leaching to groundwater for the year 2010 in Estonian-Latvian transboundary area (EEA, 2022)

It should be noted that the Nitrate Vulnerable Zone has not been identified in the Estonian-Latvian transboundary area, which is more likely to be exposed to diffuse agricultural pressure. The Nitrate Vulnerable Zone in Estonia is located in the central part of Estonia and this area coincides with high vulnerability of groundwater (in this region, mostly limestones and karst areas are common with unprotected groundwaters). About one fifth of the area is unprotected and the Northern Pandivere part is also an important groundwater supply area for the whole country. On the other hand, the most fertile soils in the country are located there, which promotes agricultural activity in this area. In Latvia, the Nitrate Vulnerable Zone is located in the central part of the country, it is delimited by administrative borders, superficially taking into account the spread of the largest agricultural lands and excluding the largest cities (Riga and Jelgava). Visually, the territories are represented in the Figure 7.

Figure 27. Nitrate vulnerability zone in Latvia and Estonia

The WFD requires the identification of significant pressures from diffuse sources of pollution. 'Significant' means that the pressure contributes to an impact that may result in failing to meet the WFD objectives of not having at least good status. In both countries, in 2021, the 3rd cycle River Basin Management Plans were prepared, in which the unified criterion for assessing the impact of diffuse pressure was adopted - it was considered that if the type of load (e.g. agricultural areas) occupies more than 50% of the GWB area, then the impact can be considered for significant. In the case of Latvia, additional criteria were also adopted (density of farm animals, diffuse pressure at the level of surface water bodies and the existence of the Nitrate Vulnerable Zone). On the other hand, if agricultural lands occupy less than 50% of the GWB area, then the impact is considered medium or insignificant (uniform criteria have not been adopted between the countries (Valters et al. 2022)).

Based on the collected data, it was concluded that the Estonian-Latvian transboundary area is not significantly affected by diffuse agricultural pressure, as its territory occupies less than 50% of the examined area. It should be taken into account 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, the type of land use and the number of livestock units in certain areas.

2.3. Groundwater abstraction

In accordance with the requirements of the Water Framework Directive (2000/60/EC), as well as the Guidance Document No.3 "Analysis of Pressures and impacts", it is important to identify significant pressures to which groundwaters are liable to to be subject, including groundwater abstraction and artificial recharge of groundwaters. To identify and estimate these pressures, 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. At the outset, it is necessary to mention that no artificial recharge of groundwaters is carried out in the Estonian-Latvian transboundary area, as a result of which this pressure type was excluded from the further pressure assessment.

In the Estonian-Latvian transboundary area, for individual, decentralized and centralized water supply, as well as for industrial and agricultural needs (including groundwater pumping from quarries for mineral extraction), 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 pilot area and is mainly exploited for decentralized water supply and individual water abstraction needs. Also, from this aquifer system groundwater is pumped in large volumes in the dolomite quarry "Ape" in order to lower the groundwater levels, for the purposes of dolomite mining. 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.

Looking at the groundwater abstraction data from the last 10-year period (2012-2021), it can be concluded that the total groundwater abstraction from drinking water supply wells have not changed significantly during the chosen time period - the total groundwater abstraction in the transboundary area has fluctuated from 5.74 thous. m^3/d to 6.97 thous. m^3/d (Figure 8). Looking at the groundwater abstraction patterns in the context of Estonia and Latvia, it can be observed that on the Latvian side there is no clear increase or decrease of total groundwater abstraction noticeable, but a slight increase can be observed on the Estonian side - from 2.60 thous. m^3/d in 2012 to 3.56 thousand. m^3/d in 2021. The most significant fluctuation in groundwater pumping volumes can be observed in the dolomite quarry "Ape" (located on Latvian side, about 3 km from the Estonian-Latvian border), where groundwater pumping volumes have ranged from 0.04 thous. m^3/d in 2016 to 4.27 thous. m^3/d in 2018, while in 2019 no groundwater pumping has not been performed.

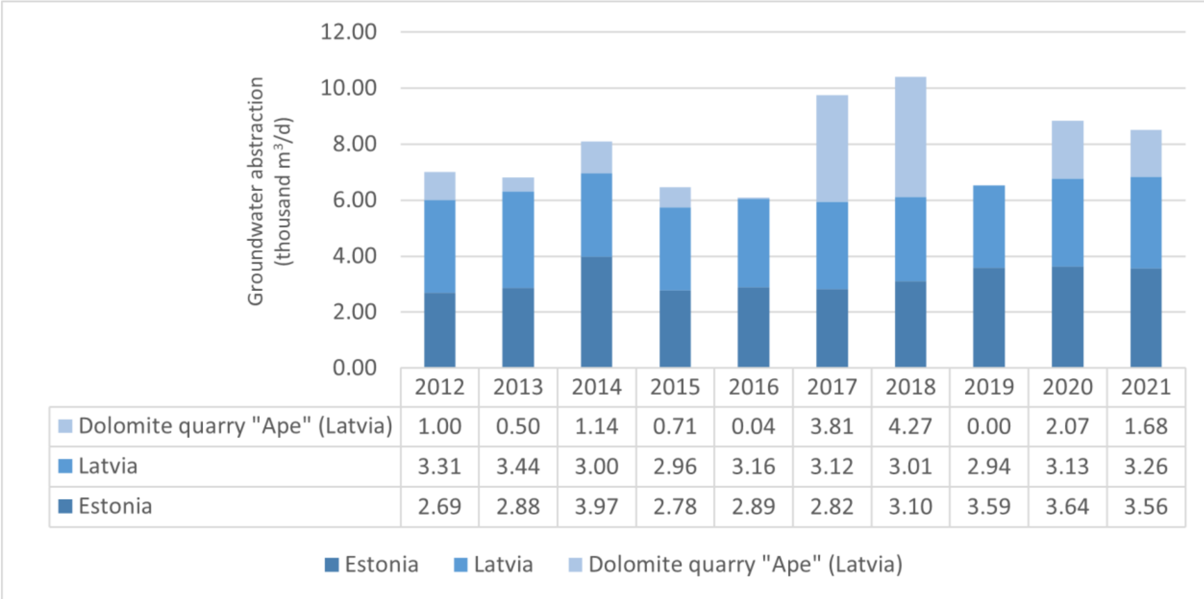
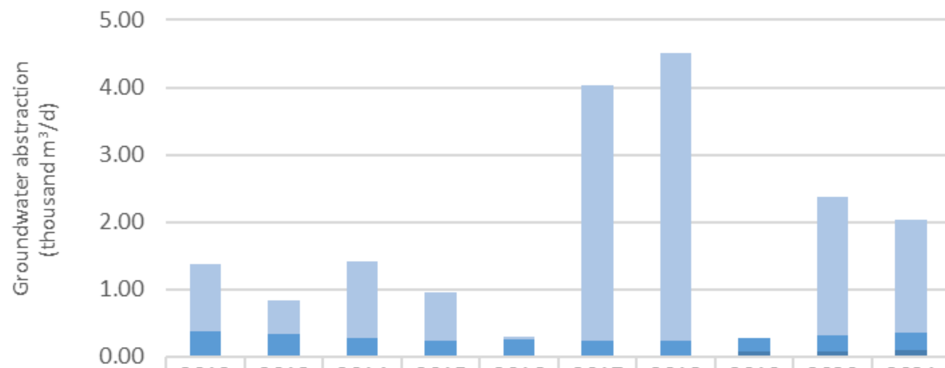


Figure 28. Total groundwater abstraction volumes in the Estonian-Latvian transboundary area in the last 10-year period (2012-2021)

In order to characterize in more detail the pressure caused by the groundwater abstraction, as well as the pressure caused by the groundwater pumping in the dolomite mining quarry "Ape", further it will be viewed in the context of the Pļaviņas-Ogre and the Aruküla-Amata groundwater aquifer systems, looking at the total annual groundwater abstraction in each country in the last 10-year time period (from 2012 until 2021), as well as in the context of maximum groundwater abstraction/pumping during the said time period.

2.3.1. Pļaviņas-Ogre aquifer system

In the last 10-year period (2012-2021), groundwater abstraction from the Pļaviņas-Ogre aquifer system in wells in the transboundary area has ranged from 0.23 thous. m^3/d (in 2014) to 0.37 thous. m^3/d (in 2012) (Figure 9). Looking at the groundwater abstraction patterns in the context of Estonia and Latvia, it can be observed that on the Latvian side the Pļaviņas-Ogre aquifer system is used for groundwater abstraction each year (abstraction volumes ranging between 210-350 m^3/d), while in the case of Estonia, groundwater abstraction from this aquifer system was resumed only in 2019 and with a very small amount - 70-100 m^3/d.



	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Dolomite quarry "Ape" (Latvia)	1.00	0.50	1.14	0.71	0.04	3.81	4.27	0.00	2.07	1.68
Latvia	0.35	0.33	0.28	0.25	0.25	0.23	0.24	0.21	0.24	0.26
Estonia	0.02							0.07	0.07	0.10

Figure 29. Total groundwater abstraction volumes in Pļaviņas-Ogre aquifer system and their maximum abstraction volumes in the period from 2012 to 2021

According to the European statistical classification of economic activities (NACE), most of the abstracted groundwater resources from Pļaviņas-Ogre aquifer system (by maximum abstraction volumes in the period from 2012 to 2021) is utilized in Mining and Quarrying sector - 85% (4 274 m^3/d) (water pumping for lowering of groundwater level in dolomite quarry "Ape"), which is followed by Water Supply and Sewerage sector - 10% (497 m^3/d) (individual and centralized water supply) and Agriculture, Forestry and Fishing sector - 4% (188 m^3/d). Less than 1% (40 m^3/d) of the abstracted groundwater resources are utilized in the Public Administration and Defence sector (Figure 10).

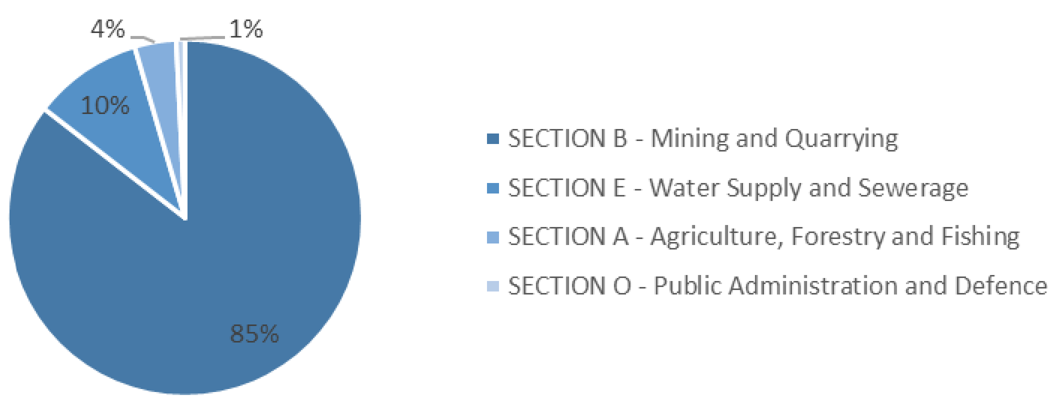


Figure 30. Utilization of obtained groundwater resources from Pļaviņas-Ogre aquifer system in the distribution by economic sectors (according to NACE classification)

The largest abstraction volumes and the most significant fluctuations in the groundwater pumping can be observed in the dolomite quarry "Ape", located about 3 km from the Estonia-Latvian border (Figure 11). As the layer of extractable dolomite deposits lie deeper than the groundwater level, the extraction can only be possible by lowering groundwater levels. The main aquifer, which determines the inflow into the quarry, is the Pļaviņas (D_3*pl*) aquifer (as permanent Quaternary groundwater aquifer has not been identified at the site or its immediate vicinity). During the last 10-year period, the volumes of groundwater pumping in dolomite quarry "Ape" have ranged from 0.04 thous. m^3/d in 2016 to 4.27 thous. m^3/d in 2018, while in 2019 no groundwater pumping has not been performed - mining volumes vary from year to year, depending on the financial capabilities of the mining company and the market demand, due to which the amount of pumped groundwater and lowering of groundwater levels also fluctuates significantly). The results of various hydrogeological researches, as well as modeling results (SIA "Zemes Puse, 2015; SIA "Firma L4", 2006) indicate that the radius of the depression cone around the quarry "Ape" could reach up to 3.2 km at the maximum lowering of the groundwater level in the quarry (final stage of extraction by lowering the water level by 17-18 m). However, it should be emphasized that in this case a larger depression cone will form around the quarry itself and only within a radius of 1 km, because of which a decrease in groundwater level in the Pļaviņas (D_3*pl*) aquifer by 2 m will be observed. The resulting impact on the transboundary area at regional level will be minimal and localized.

Similar results were obtained during project report "Transboundary impacts as a result of exploitation of groundwater resources in Polish-Ukrainian and Estonian-Latvian pilot areas" - changes were mainly observed near the quarry, but no significant changes in transboundary flow pattern were observed. The modeling results confirmed that even with maximum groundwater pumping rates, no significant impact on transboundary groundwater resources could be observed. Nevertheless, it should be noted that the current hydrogeological model of the Estonian-Latvian transboundary area represents regional scale, and therefore, it is impossible to accurately reflect local groundwater changes (Solovey et al., 2022).

Looking at the spatial locations of groundwater abstraction points in the last 10-year period, it can be concluded that the largest number of them 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 has been identified (Figure 11). The largest maximum groundwater abstraction and pumping can be observed in the dolomite quarry "Ape", where in 2018 it reached 4.27 thous. m^3/d - in this area groundwater abstraction practically every year exceeds 500 m^3/d.

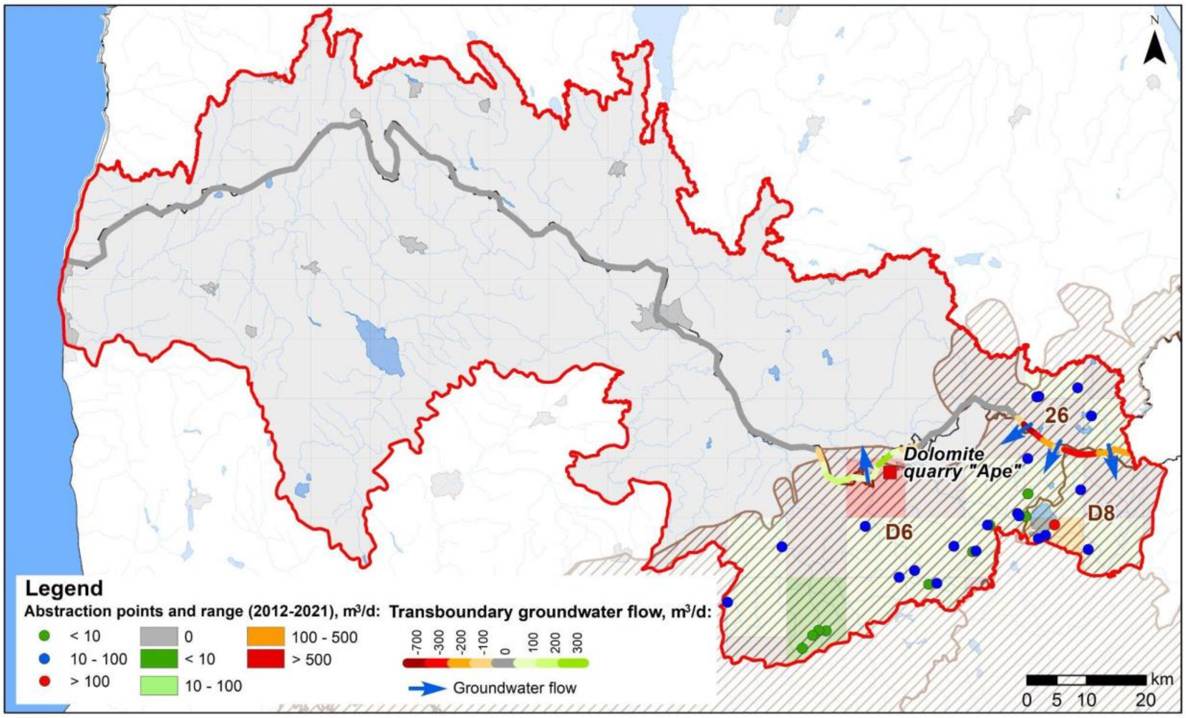


Figure 31. Groundwater abstraction points in Pļaviņas-Ogre aquifer system and their maximum abstraction volumes in the period from 2012 to 2021

As described above and also concluded in previous project reports, initial assessment shows that groundwater abstraction and pumping from the Plaviņas-Ogre aquifer system cannot significantly affect the hydrogeological conditions in the Estonian-Latvian transboundary area. The assessment of the groundwater abstraction pressure in the Latvian-Estonian transboundary area against the total groundwater resources for the Pļaviņas-Ogre aquifer system is carried out in Chapter 4.

2.3.2. Aruküla-Amata aquifer system

In the last 10-year period (2012-2021), groundwater abstraction from the Aruküla-Amata aquifer system in the transboundary area has ranged from 5.50 thous. m^3/d (in 2015) to 6.69 thous. m^3/d (in 2014) and it does not show significant upward or downward trend during the chosen time period (Figure 12). Looking at the groundwater abstraction patterns in the context of Estonia and Latvia, it can be observed that on the Latvian side the volumes of groundwater abstraction are practically stationary from year to year, varying from 2.71 thous. m^3/d up to 3.11 thous. m^3/d, while on the Estonian side, a steady increase in the amount of groundwater abstraction can be observed - from 2.66 thous. m^3/d (in 2012) up to 3.47 thous. m^3/d (in 2021); the exception is 2014, in which the total amount of abstraction reached 3.97 thous. m^3/d.

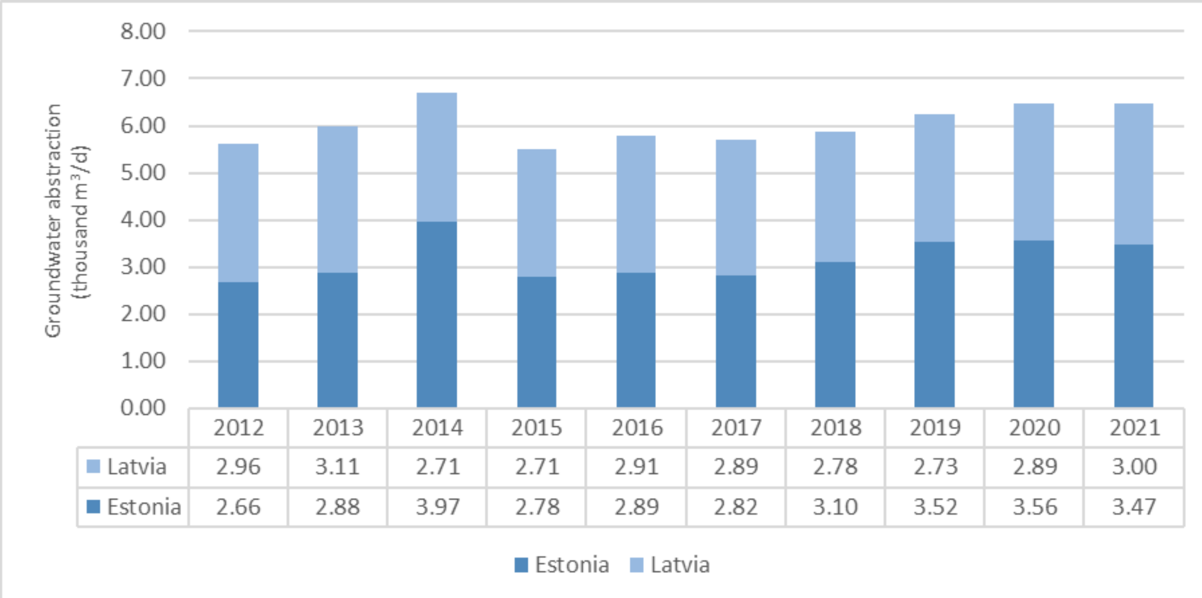


Figure 32. Total groundwater abstraction volumes in Aruküla-Amata aquifer system and their maximum abstraction volumes in the period from 2012 to 2021

According to the European statistical classification of economic activities (NACE), most of the abstracted groundwater resources from Aruküla-Amata aquifer system (by maximum abstraction volumes in the period from 2012 to 2021) is utilized in Water Supply and Sewerage sector - 76% (8 455 m^3/d) (individual and centralized water supply), followed by Agriculture, Forestry and Fishing sector - 15% (1 718 m^3/d). Almost equally abstracted groundwater resources are utilized in Manufacturing and Electricity, Gas, Steam and Air Conditioning sectors - 4% (443 m^3/d and 428 m^3/d, respectively). About 1% (97 m^3/d) are utilized in other sectors, for example, Accommodation and Food Service Activities (0.4%, 47 m^3/d), Human Health and Social Work Activities (0.2%, 24 m^3/d) and Wholesale and Retail Trade (01%, 13 m^3/d), among others (Figure 13).

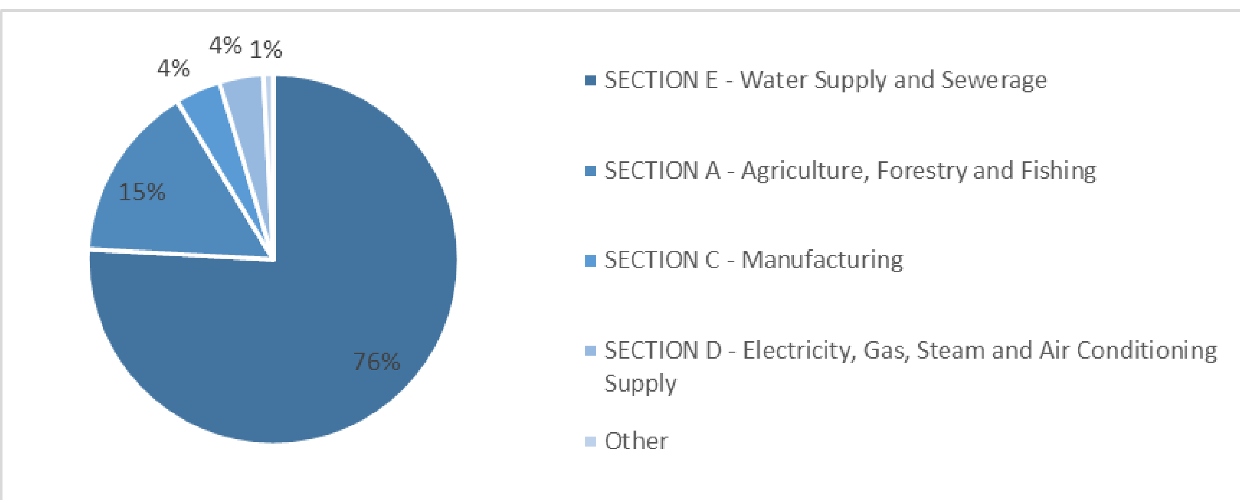


Figure 33. Utilization of obtained groundwater resources from Aruküla-Amata aquifer system in the distribution by economic sectors (according to NACE classification)

Looking at the spatial locations of groundwater abstraction points in the last 10-year period, areas with intensive groundwater abstraction (greater than 500 m^3/d) are located near the largest cities of the Estonian-Latvian transboundary area (Figure 14). In the vicinity of Tõrva city, the total amount of groundwater abstraction during the last 10-year period has fluctuated from 1.85 thous. m^3/d up to 3.11 thous. m^3/d, while in the vicinity of Valga and Valka cities, the total amount of groundwater abstraction has fluctuated from 2.19 thous. m^3/d up to 3.33 thous. m^3/d. Maximum groundwater abstraction from individual wells above 100 m^3/d can be observed in the vicinity of Abja-Paluoja city (116.38 m^3/d in 2021), Ape city (108.85 m^3/d in 2020) ar Rūjiena city (110.38-144.26 m^3/d throughout the period).

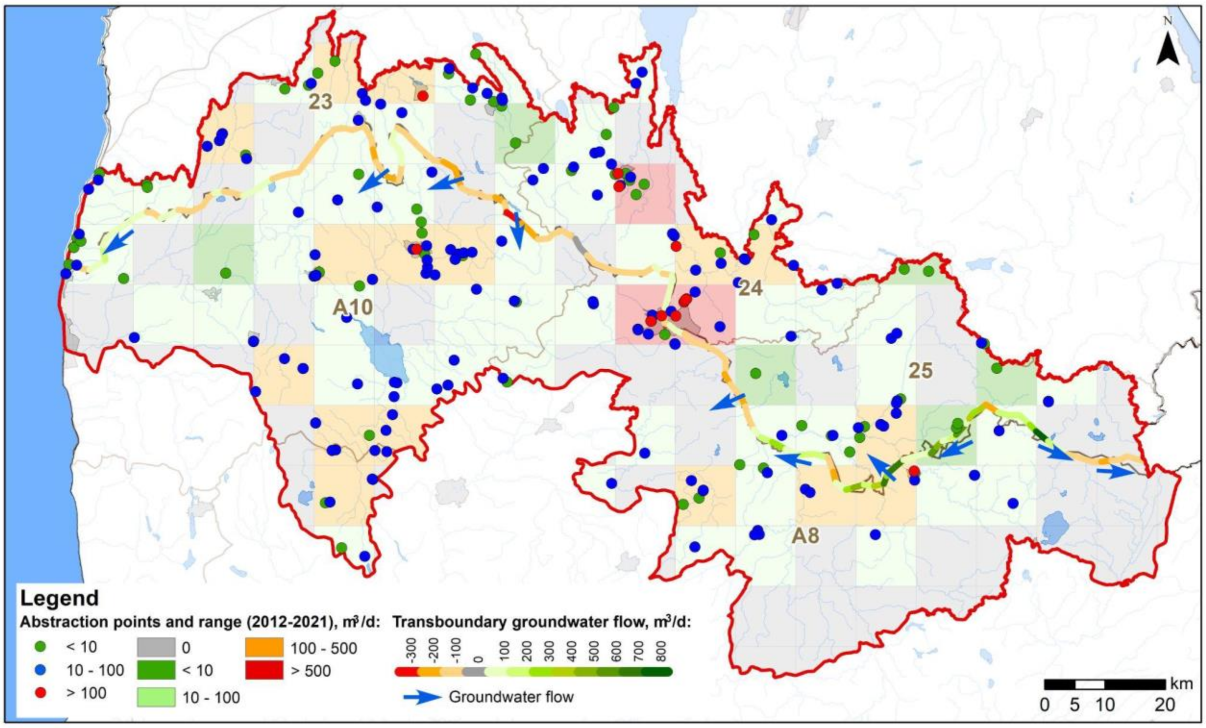


Figure 34. Groundwater abstraction points in Aruküla-Amata aquifer system and their maximum abstraction volumes in the period from 2012 to 2021

As described above and also concluded in previous project reports, initial assessment shows that groundwater abstraction and pumping from the Aruküla-Amata aquifer system cannot significantly affect the hydrogeological conditions in the Estonian-Latvian transboundary area. The assessment of the groundwater abstraction pressure in the Latvian-Estonian transboundary area against the total groundwater resources for the Aruküla-Amata aquifer system is carried out in Chapter 4.

3. Groundwater vulnerability to pollution and depletion

3.1 Methodologies for creating a groundwater vulnerability map in the Estonian-Latvian pilot area

There are multiple aquifers and aquifer systems in the Estonian-Latvian transboundary area that play multiple purposes according to available resources and groundwater quality. Confined aquifers are typically used for centralized water supply and as a drinking water source because of extensive available resources and low vulnerability – confined aquifers typically are situated in depths larger than a few tens of meters and are covered by clayey layers that protects water quality. However, shallow unconfined groundwater is important for ecosystems and in rural areas it is also used as a local water supply for individual households. Moreover, shallow unconfined aquifer is the main source of recharge for confined groundwater and act as a natural filter that retain contaminants in the water movement from the infiltration in unsaturated zone to the recharge in confined aquifers, thus the vulnerability of the unconfined aquifer is of great importance and must be assessed.

3.1.1 Vertical infiltration time calculation method

A simplified method is used to assess natural vulnerability of shallow unconfined aquifer that is based on Bindemann's formula and modified by Macioszczyk (Macioszczyk, 1999) as this is the same approach used in the Ukrainian-Polish transboundary area as well as in other studies in Poland (Witkowski & Kowalczyk, 2004; Liszkowska, 2017). For EE-LV transboundary area this approach assess travel time of theoretical pollutant through unsaturated zone to the water table according to the following equation:

$$t = \frac{m W_o}{\sqrt[3]{\omega^2 k_z}}$$

where:

t – travel time [T];
m – thickness of the unsaturated zone [L];
W0 – average moisture content of the strata in the unsaturated zone;
W – infiltration intensity [L/T];
k – vertical hydraulic conductivity of the unsaturated zone [L/T];

Travel times were calculated for the whole EE-LV transboundary area within raster cells in size of 250 by 250 meters. The data that was in different resolutions and/or in different projections were transformed and warped accordingly to have a common grid and projection. The Baltic TM (EPSG 25884) was used as a target projection. The final vulnerability map was prepared by translating the calculated travel times into vulnerability class using the same values for classes as used in UA-PL transboundary area (Table 7).

Table 28. Vulnerability classes and corresponding vertical travel times in unsaturated zone

Vulnerability ID	Vulnerability class	Vertical travel time through unsaturated zone (years)
1	Very high	<5
2	High	5-25
3	Average	25-50
4	Low	50-100
5	Very low	>100

The equitation requires data that was compiled to the EE-LV pilot area and is characterized below.

Thickness of the unsaturated zone

Thickness of the unsaturated zone product is a result from the hydrodynamic hydrogeological model for the Estonian-Latvian transboundary area. The model is built using MODFLOW-NWT software with ModelMuse as a graphical user interface. The resolution of unsaturated zone thickness product is determined by the resolution of the hydrogeological model which has grid cells with sizes of 250 to 1000 meters: in the transboundary area most of the cells are 250 meters in size while in the outer part (or buffer) cells are coarser. The model includes interaction with surface water bodies – lakes and streams that improves realistic representation of unsaturated zone. The average thickness of unsaturated zone product is 7.75 m and median value is 5.13 m, while almost 30% of all cells in the transboundary area have unsaturated zone thickness less than 0.5 meters (Figure 15). The shortest unsaturated zones are found in the vicinity of surface waters (lakes, rivers, streams) and wetlands (peat bogs, mires), thus a particular pattern of unsaturated zone thicknesses is formed (Figure 16).

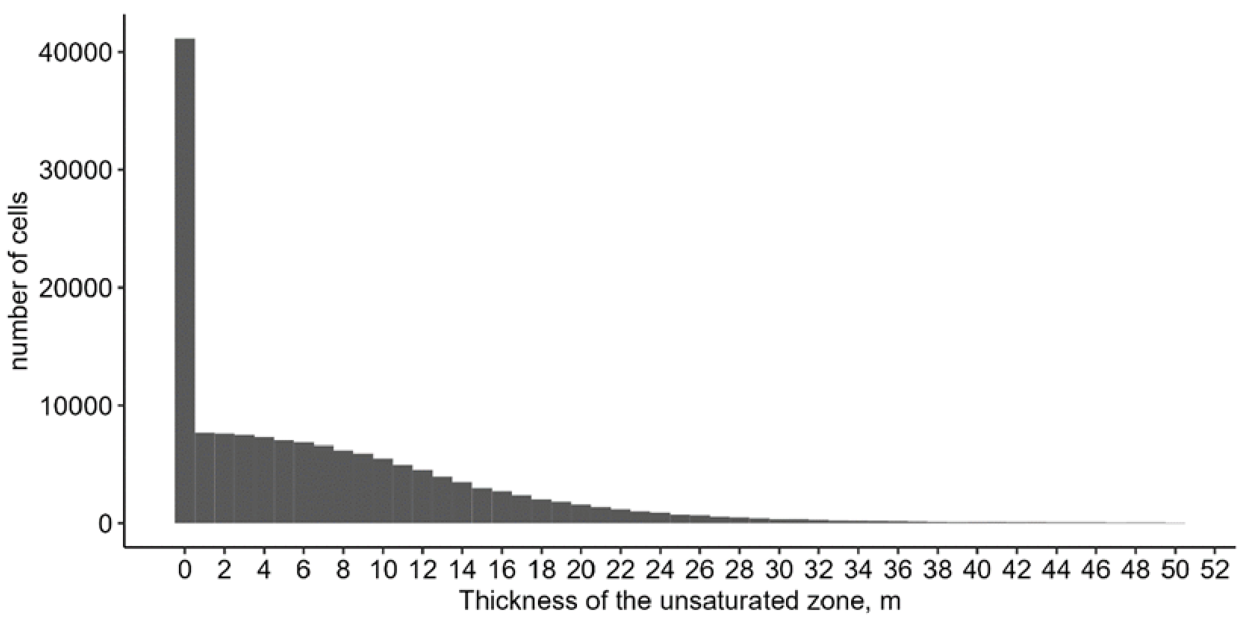


Figure 35. The histogram, of the thicknesses of unsaturated zone

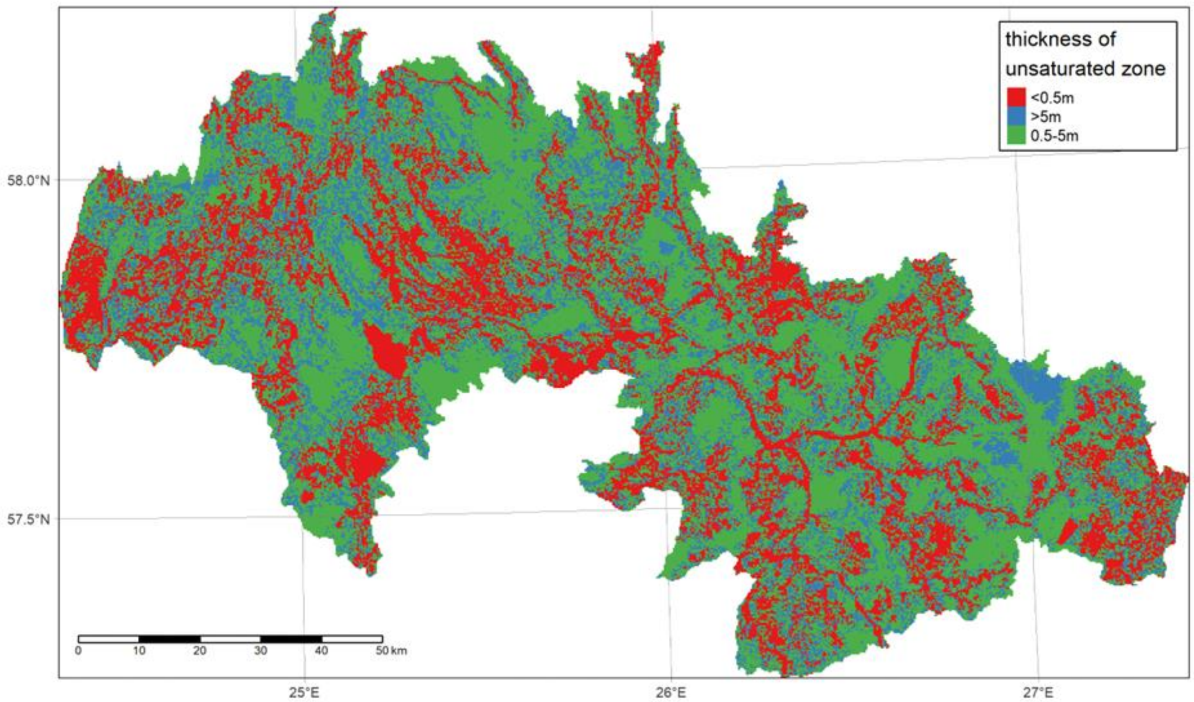


Figure 36. Thickness of the unsaturated zone in the Estonian-Latvian transboundary area

Infiltration intensity

Recharge at the ground surface was used as a proxy that represents vertical infiltration intensity. The recharge used is a resulting product from the EE-LV transboundary hydrodynamic groundwater model (the same used for the unsaturated zone thickness). The average recharge intensity in the EE-LV transboundary area is 1.672*10-4 m/d (Figure 17).

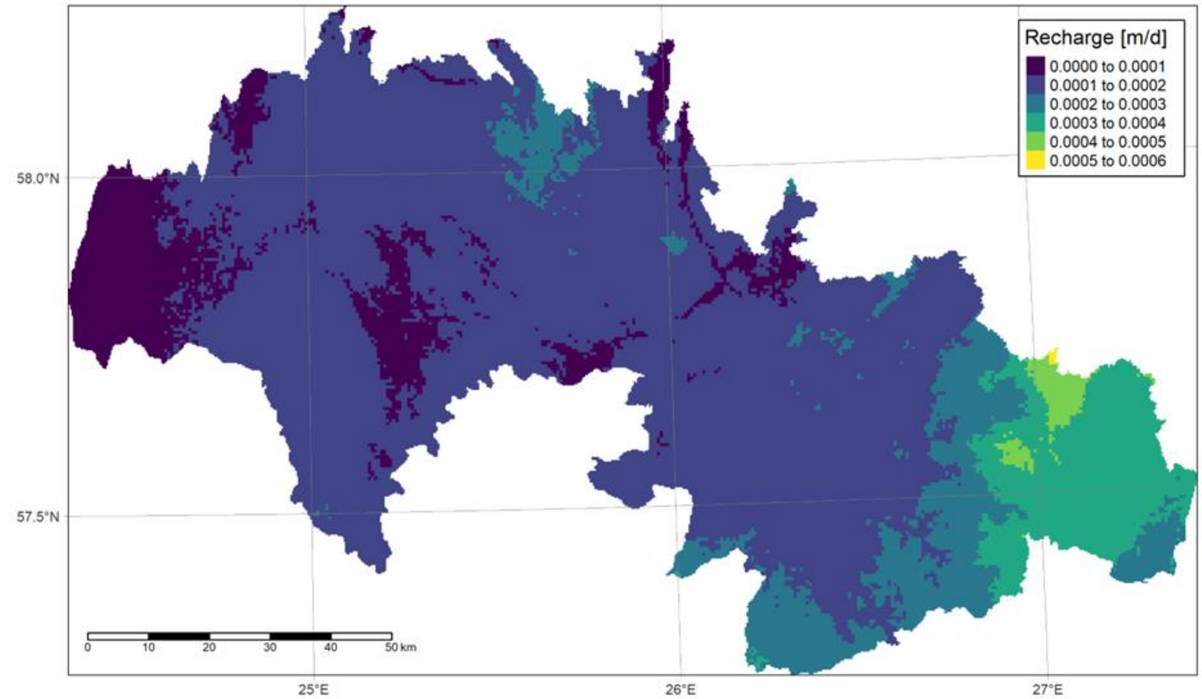


Figure 37. Groundwater recharge in the Estonian-Latvian transboundary area

Hydraulic conductivity of the unsaturated zone

Vertical hydraulic conductivity (k) of the unsaturated zone is required to calculate vertical travel time according to Bindeman's equation, however, it is challenging to have accurate k values for the whole transboundary territory. To account for the whole area, a generalized Quaternary lithology map was used as a backbone with estimated values for each generalized class. In total, seven generalized classes of Quaternary lithology were established for the EE-LV transboundary area by compiling and unifying national Quaternary maps of Estonia and Latvia (Figure 18).

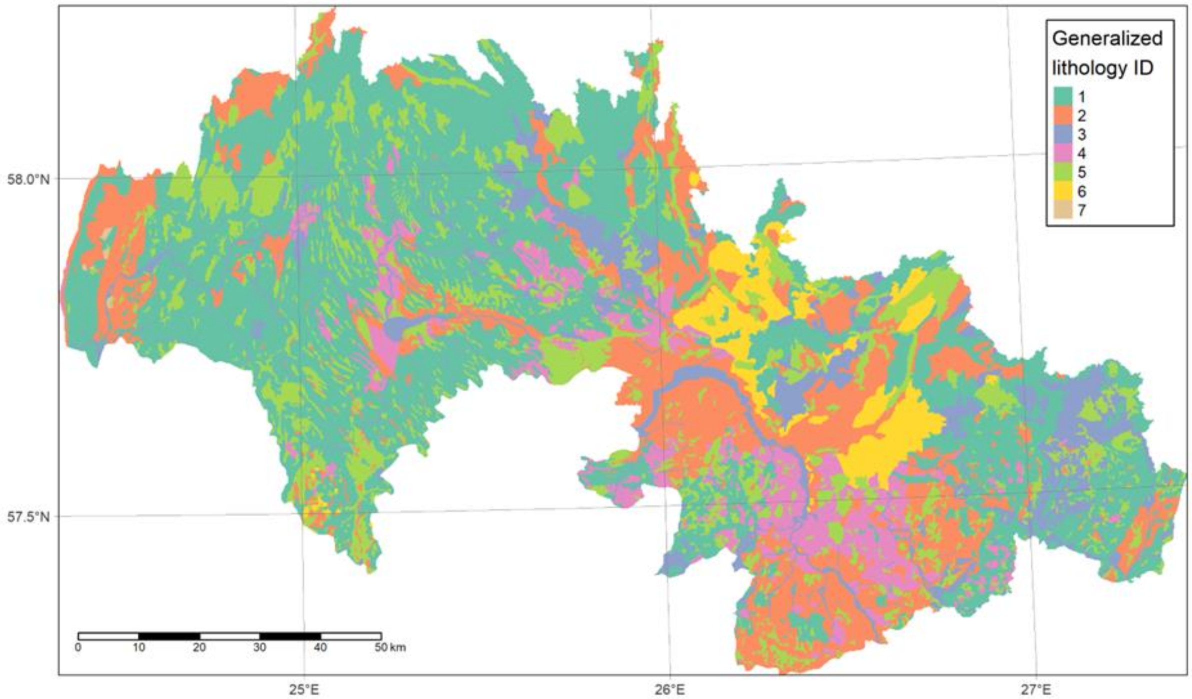


Figure 38. The generalized Quaternary lithology for the EE-LV transboundary area (for explanation of lithology ID's please see Table 8)

Hydraulic conductivity values were estimated for each of the seven lithology classes using historical reports and expert judgment. Moreover, as it is impossible to establish a single value for each of the lithological classes, a range of the k values were suggested (Table X-k) to account for minimal and maximal values, as well as to establish optimum values to represent supposed "average" hydraulic conductivity. All three values (min, max and optimum) are further used to construct three versions of vulnerability map to account for variability of hydraulic conductivities.

Table 29. Hydraulic conductivity (k) values estimated for the generalized lithological layers in the EE-LV transboundary area

Lithology class id	Lithology (generalized)	estimated lowest value of k m/d	estimated highest value of k m/d	estimated optimum value of k m/d
1	glacial till	0.0001	0.01	0.001
2	sand, fine sand	0.01	10	0.5
3	peat	0.01	0.1	0.01
4	clay, silty clay	0.000001	0.01	0.00001
5	sand, gravel	1	10	4
6	silt, clayey silt, silty sand	0.001	0.2	0.01
7	other (bedrock, technogenic)	0.0001	1	0.01

Volumetric humidity

Bindeman's equation requires the average volumetric humidity of the unsaturated zone that is often not measured directly. Thus, to cover the whole EE-LV transboundary area, ERA5-Land reanalysis products were used – more specifically, four products namely "Volumetric soil water layer" for layers 1, 2, 3 and 4 that represents volumetric soil water content in depths of 0-7 cm, 7-28 cm, 28-100 cm and 100-289 cm respectively. ERA5-Land is a global reanalysis model with a resolution of 0.1 degrees and it must be noted that the dataset is a model and is not a precise representation of the real natural values (especially for variables that represent underground processes) but is useful for regional studies as a general representation.

Monthly values for the four ERA5-Land soil moisture products were acquired from Copernicus Climate Data Store (https://cds.climate.copernicus.eu/) for the time period of 1982-01-01 to 2020-11-30. The data was aggregated temporarily and by the four products to have a single average value for each given cell, thus it represents average soil moisture up to depths of 2.89 meters. The average soil moisture content for the EE-LV transboundary area is 0.34, while the value does not change much spatially (Figure 19).

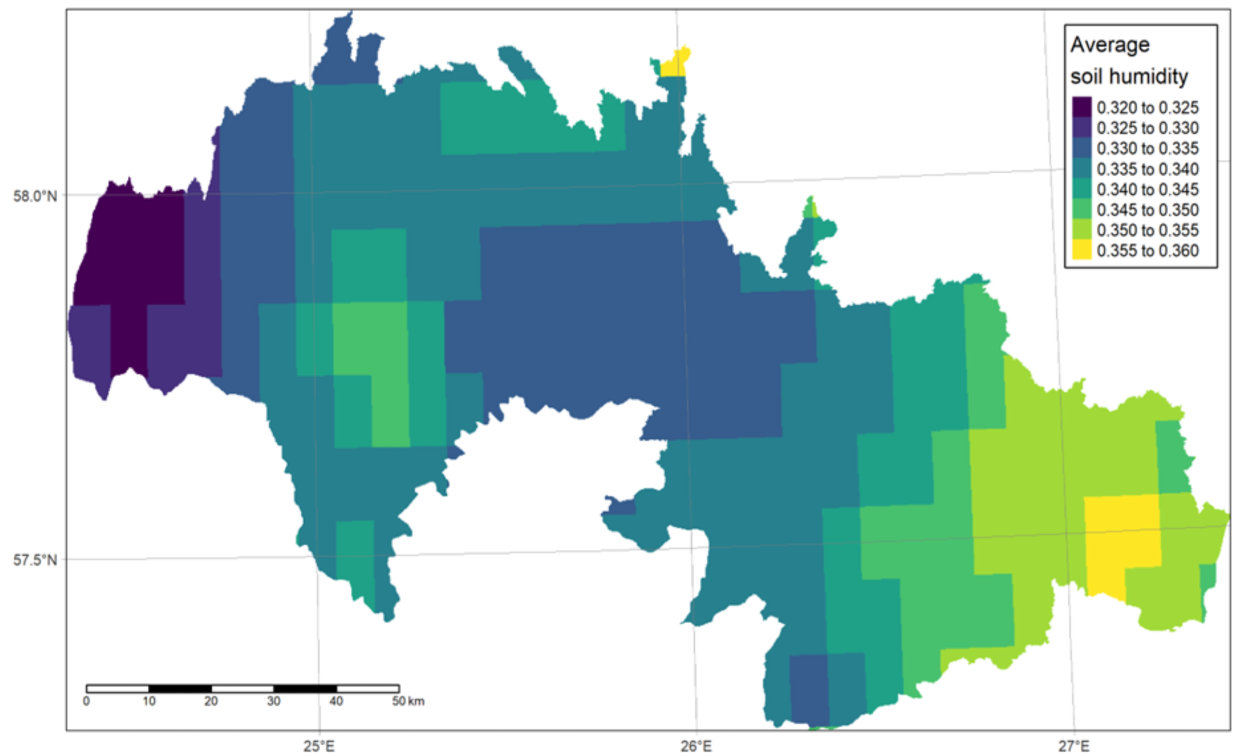


Figure 39. Averaged soil moisture for the EE-LV transboundary area according to ERA5-Land reanalysis dataset

3.1.2 DRASTIC method

The U.S. Environmental Protection Agency developed the DRASTIC method to assess groundwater vulnerability to contamination (Aller et al. 1987). The DRASTIC method uses seven hydrogeological parameters used to determine groundwater vulnerability: depth to water, net recharge, aquifer media, soil media, topography, impact of the vadose zone and hydraulic conductivity (Table 9; Aller et al. 1987).

Table 30. The DRASTIC method parameters and their weights

Parameter	Description	Weight
Depth to water (D)	Represents the depth from the ground surface to the water table. The deeper the water table, the lower the contamination risk.	5
Net recharge (R)	Refers to the amount of water that reaches the water table by infiltrating through the ground surface and the vadose zone. Higher recharge indicates a larger potential for groundwater contamination.	4
Aquifer media (A)	Represents the properties of the sediments forming the aquifer. Larger grain sizes and more fractures and openings mean higher permeability and lower attenuation capacity of the aquifer media.	3
Soil media (S)	Refers to the uppermost weathered part of the vadose zone that determines the amount of water that can infiltrate into the ground. Clays and organic material can limit contaminant migration.	2
Topography (T)	Represents the slope of the land surface and determines the likelihood of whether a pollutant will run off or remain on the surface long enough to infiltrate.	1
Impact of the vadose zone (I)	Refers to the sediments' type in the unsaturated zone above the water table and determines the attenuation of the contaminants. Higher permeability allows faster contaminant movement.	5
Hydraulic conductivity (C)	Represents the ability of the aquifer to transmit water and the rate at which a contaminant moves in an aquifer. Higher hydraulic conductivity is associated with a higher contamination risk.	3

Each parameter is classified either into ranges or into medium types based on the contribution to the overall vulnerability based on the impact on pollution potential. The rating range is 1 to 10, where 1 means the lowest vulnerability and 10 the highest. All parameters have weights ranging from 1 to 5. The final vulnerability index is a weighted sum of the seven parameters, where a higher vulnerability index refers to a greater groundwater contamination risk:

$$D_i = \sum_{j=1}^{7} \quad (W_j \times R_j)$$

where: D_i – vulnerability index for a mapping unit, W_j – weight of parameter j, R_j – rating of parameter j.

The DRASTIC method was used to calculate the vulnerability to pollution of the Quaternary aquifer in the Estonian-Latvian TBA. For this, all seven parameters of the method were used, their ratings are given in Table 10. The data sources for the parameters are given in Table 11.

Table 31. Parameters and ratings used to calculate groundwater vulnerability of the Quaternary aquifer

(D) Depth to water		(R) Net recharge		(A) Aquifer media		(S) Soil media	
Range (m)	Rating	Range (mm/y)	Rating	Type	Rating	Type	Rating
0–1.5	10	0–50	1	Clay	4	Clay	1

(D) Depth to water		(R) Net recharge		(A) Aquifer media		(S) Soil media	
1.5–5	9	50–100	3	Bedrock	4	Bedrock	2
5–10	7	100–175	6	Peat	4	Peat	6
10–15	5	175–250	8	Gravel	6	Gravel	6
15–20	3	> 250	9	Sand	6	Sand	7
20–30	2			Till	4	Till	8
>30	1						
(T) Topography		**(I) Impact of the Vadose zone**		**(C) Hydraulic conductivity**			
Slope (%)	Rating	Type	Rating	Type		Rating	
0–2	10	Clay	1	Clay (K=0,000001–0,01)		1	
2–6	9	Bedrock	10	Bedrock (K = 0,0001–1)		1	
6–12	5	Peat	8	Peat (K = 0,01–0,1)		1	
12–18	3	Gravel	8	Gravel (K=10–50)		2	
>18	1	Sand	8	Sand (K=0,01–10)		2	
		Till	6	Till (K=0,0001–0,01)		1	

Table 32. Data sources for the DRASTIC parameters

Parameter	Data source	Data format
D	Estonian-Latvian transboundary area hydrogeological model	Raster data
R	Estonian-Latvian transboundary area hydrogeological model	Raster data
A	Generalized EE-LV Quaternary sediments map	Vector data, 1:200 000
S	Generalized EE-LV Quaternary sediments map	Vector data, 1:200 000
T	Digital elevation model from Lidar elevation data	Raster data
I	Generalized EE-LV Quaternary sediments map	Vector data, 1:200 000
C	Generalized EE-LV Quaternary sediments map	Vector data, 1:200 000

The depth to water (D) parameter (Figure 20) is used to assess the pathway of the pollutant from the ground surface to the water table. The piezometric surface of the Quaternary aquifer from the EE-LV hydrogeological model was used to calculate the D-parameter. The piezometric surface was subtracted from the DEM of the ground surface (Lidar data). As a result, the resulting depth to water values were classified into ranges, a larger vulnerability rating indicates a groundwater level near ground surface. Areas with a rating 1 cover 2,4% of the

TBA, rating 2 – 4,6%, rating 3 – 6,6%, rating 5 – 12,8%, rating 7 – 22,4%, rating 9 – 21,9% and rating 10 cover 29,3% of the TBA.

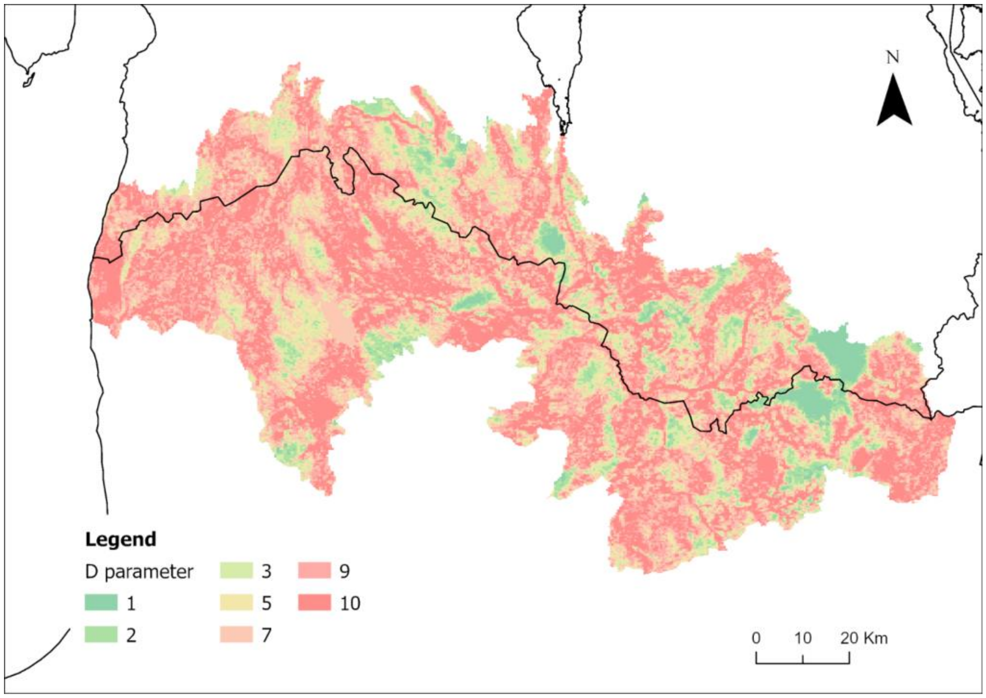


Figure 40. Depth to water (D) parameter ratings in the Estonian-Latvian TBA.

The net recharge (R) parameter (Figure 21) considers the average amount of water which has infiltrated during the year. For the R-parameter, net recharge data from the EE-LV hydrogeological model were used. A higher vulnerability rating for the parameter indicates a higher recharge value and a higher risk of contamination. Areas with a rating 1 cover 42,8% of the TBA, rating 3 – 45,6%, rating 6 – 11,5% and rating 8 cover 0,1% of the TBA.

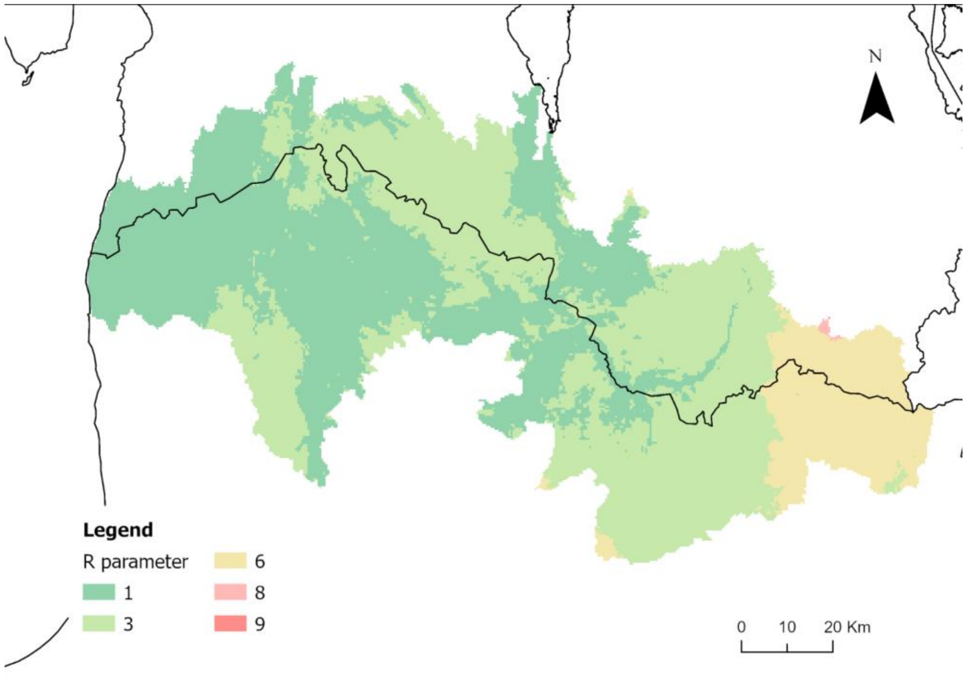


Figure 41. Net recharge (R) parameter ratings in the Estonian-Latvian TBA.

The aquifer media (A) parameter (Figure 22) describes the properties of the rock forming the Quaternary aquifer, such as lithology, texture and structure. These properties affect the transport of pollutants within the aquifer. The generalized Quaternary sediment map of the Estonian-Latvian TBA (see Figure 18) was used for the assessment of the A-parameter. In order to harmonize and generalize the data, new classes for the Quaternary sediment types were created. Aquifer type with a higher pollution risk receives a higher vulnerability rating. Areas with a rating 4 cover 71,4% and rating 6 cover 28,6% of the TBA.

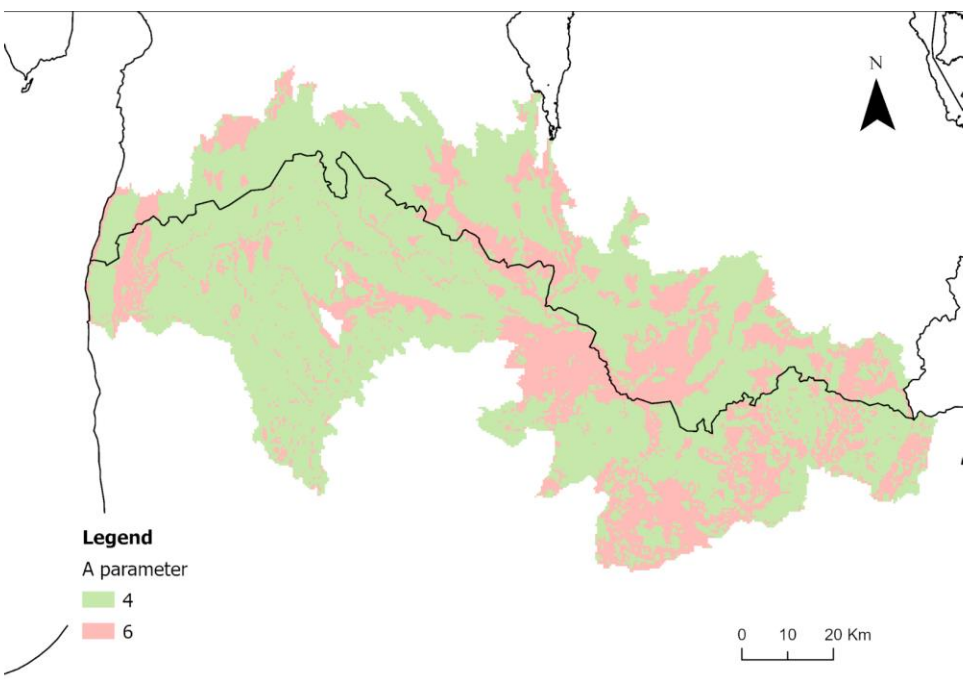


Figure 42. Aquifer media (A) parameter ratings in the Estonian-Latvian TBA.

In the DRASTIC methodology, the soil media (S) parameter (Figure 23) describes the properties of the uppermost and most biologically active part of the aeration zone, i.e. the soil. More precisely, the part about 2 meters deep from the surface is examined. Due to the lack of comprehensive soil maps on the transboundary area, the generalized map of the Quaternary sediments was used instead. Moreover, in areas of Quaternary sediments, the soil properties correlate with the Quaternary sediment properties. The sediment types with a higher risk of pollution receive a higher vulnerability rating. Areas with a rating 1 cover 11,3% of the TBA, rating 6 – 43,3%, rating 8 – 44,8% and rating 10 cover 0,5% of the TBA.

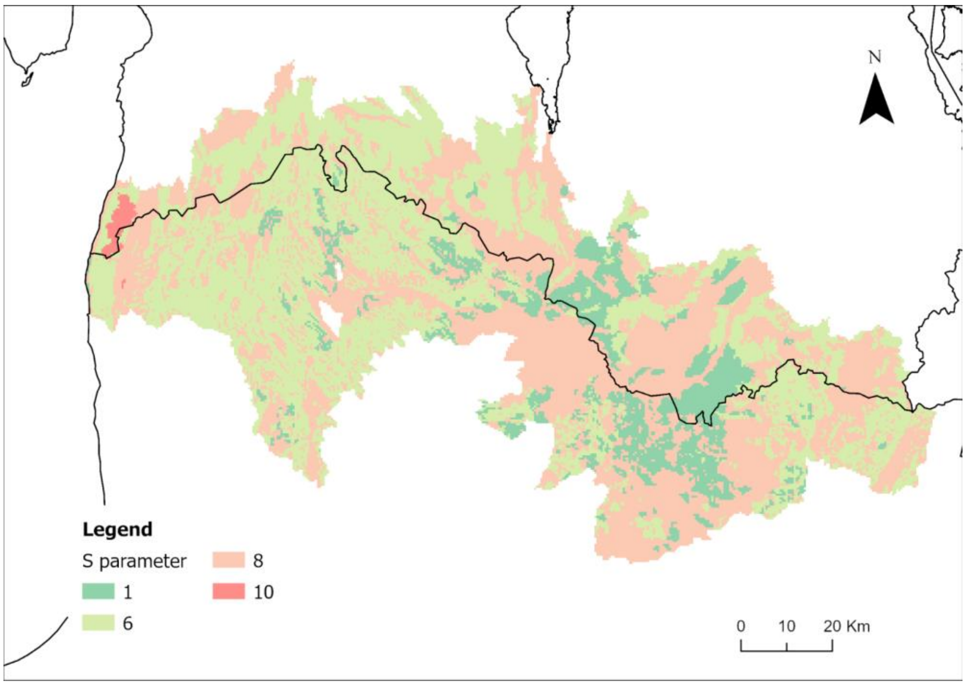


Figure 43. Soil media (S) parameter ratings in the Estonian-Latvian TBA.

The topography (T) parameter (Figure 24) describes the slope of the land surface. The parameter assesses the likelihood of whether a pollutant will run off or remain on the surface long enough to infiltrate. For the analysis, a digital elevation model from Lidar elevation data was used. Areas with a steeper slope will receive a smaller vulnerability rating. Areas with a rating 3 cover 0,03% of the TBA, rating 5 – 1,75%, rating 9 – 35,31% and rating 10 cover 62,91% of the TBA.

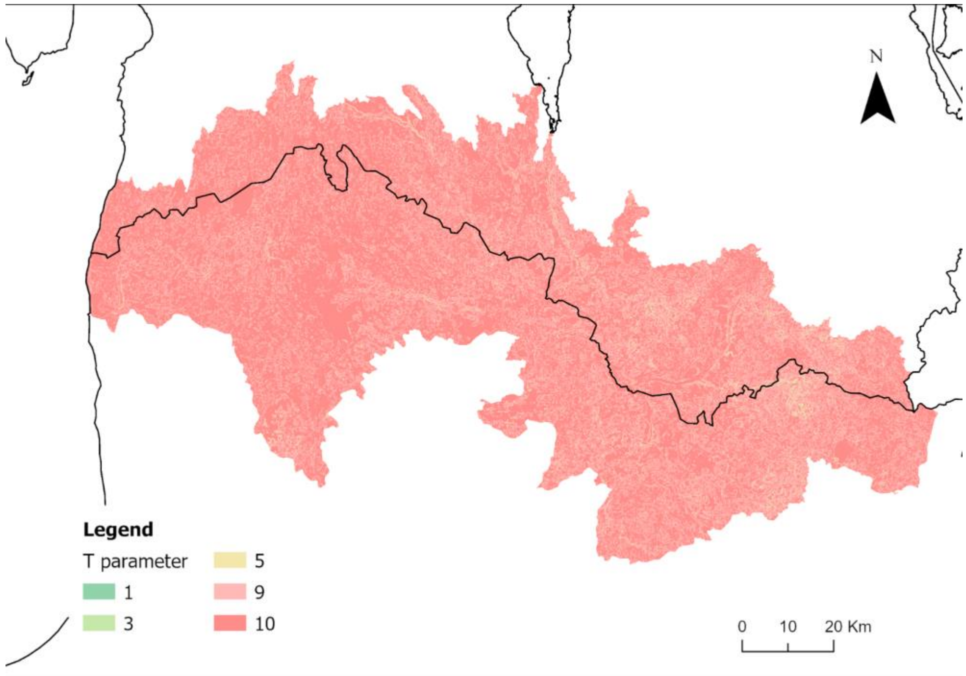


Figure 44. Topography (T) parameter ratings in the Estonian-Latvian TBA.

The vadose zone (I) parameter (Figure 25) is used to assess the impact of the unsaturated zone above the water table. The attenuation of the contaminants is determined by the sediments' type. For the analysis, the generalized Quaternary map of the transboundary area was used. Sediments with a higher risk for pollution will receive a higher vulnerability rating. Areas with a rating 3 cover 11,3% of the TBA, rating 6 – 43,9% and rating 8 cover 44,8% of the TBA.

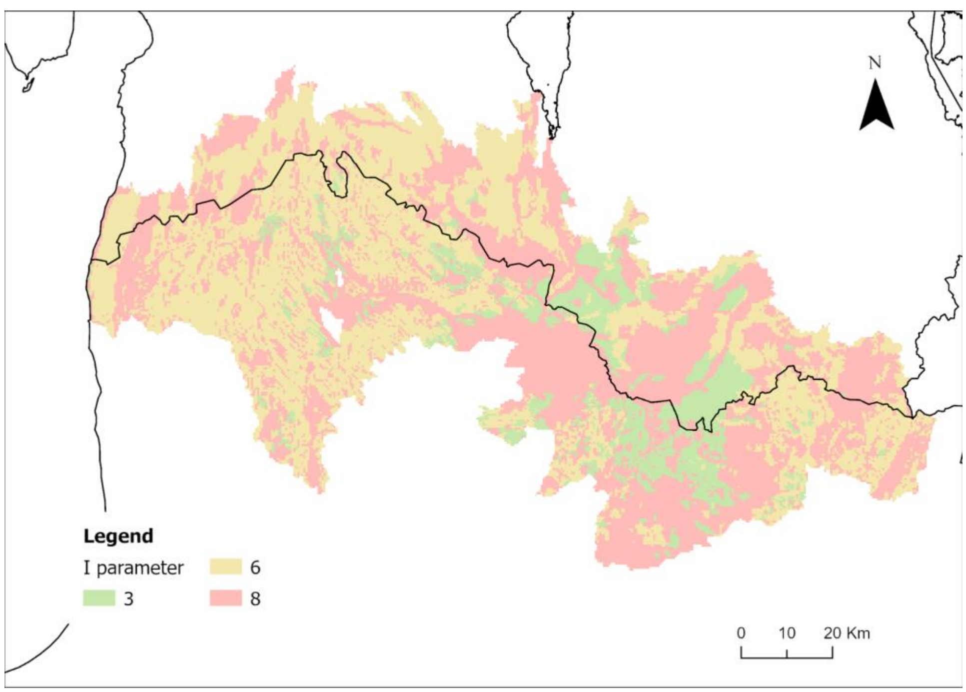


Figure 45. Vadose zone (I) parameter ratings in the Estonian-Latvian TBA.

The hydraulic conductivity (C) parameter (Figure 26) describes the ability of the aquifer to transmit water. Hydraulic conductivity values used for different Quaternary sediment types are given in Table 2. A higher hydraulic conductivity value receives a higher vulnerability rating. Areas with a rating 1 cover 71,4% and rating 2 cover 28,6% of the TBA.

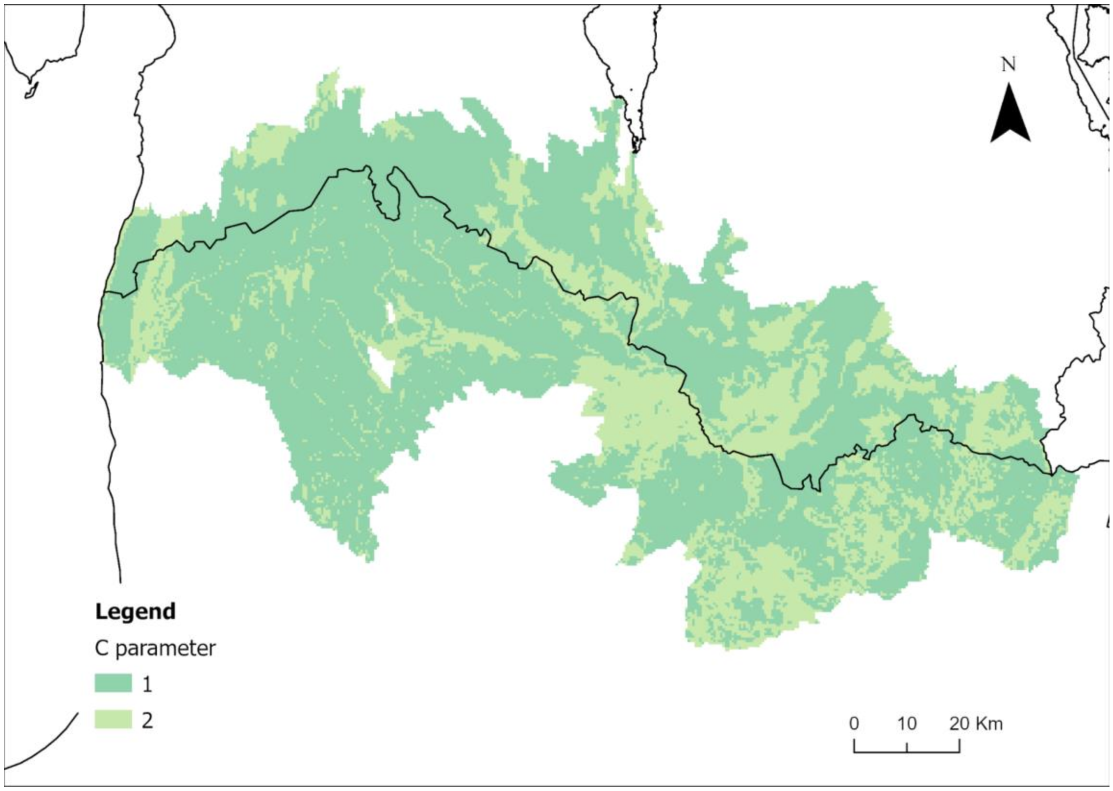


Figure 46. Hydraulic conductivity (C) parameter ratings in the Estonian-Latvian TBA.

The final vulnerability index is a sum of the ratings of the seven parameters multiplied by their weights. A higher vulnerability index refers to a greater groundwater contamination risk The resulting groundwater vulnerability indexes are divided into five classes according to their values. Hamza et al. (2015) divides the percentage range of minimum and maximum values of the vulnerability index into five equal divisions: "very low" (10.00%–28.99%), "low" (29.00%–46.99%), "medium" (47.00%–64.99%), "high" (65.00%–82.99%) and "very high" (83.00%–100%).

3.1.3 The modified DRASTIC method

The DRASTIC method has been widely used around the world in unconfined aquifers (Jang et al. 2017, Maqsoom et al. 2021, Ahmed et al. 2022). However, in regions with a complex Quaternary cover above the first bedrock aquifer, the original DRASTIC method overestimates the vulnerability of areas with groundwater overflow and regions where groundwater is occasionally confined. In areas with a confined aquifer, the method does not consider the thickness of the vadose zone or, in this study area, the thickness of the Quaternary deposits as well as their hydraulic characteristics.

Therefore, in the Estonian-Latvian TBA, a modified DRASTIC method was used to assess the groundwater vulnerability of the first bedrock (main useful) aquifer (Männik et al, in press). In the method, three parameters of the DRASTIC method are modified to increase the accuracy of vulnerability assessment in areas with a Quaternary sediment layer: the depth to water (D) parameter, the soil type (S) parameter, and the impact of the vadose zone (I) parameter. The modified parameters and their weights are given in Table 12.

Table 33. The modified DRASTIC method parameters and their weights

Parameter	Description	Weight
Depth to water (D)	Depth of the piezometric head compared to the bedrock surface. The vulnerability of the aquifer is higher in areas where the piezometric head is above the bedrock surface and lower in areas where it is below the bedrock surface.	5
Net recharge (R)	Refers to the amount of water that reaches the water table by infiltrating through the ground surface and the vadose zone. Higher recharge indicates a larger potential for groundwater contamination.	4
Aquifer media (A)	Represents the properties of the sediments forming the aquifer. Larger grain sizes and more fractures and openings mean higher permeability and lower attenuation capacity of the aquifer media.	3
Quaternary sediment type (S)	Refers to the properties of the Quaternary sediments above the main useful aquifer, which determine the amount of water that can infiltrate into the ground.	5
Topography (T)	Represents the slope of the land surface and determines the likelihood of whether a pollutant will run off or remain on the surface long enough to infiltrate.	1
Thickness of the Quaternary sediments (I)	Refers to the path of the pollutant from the ground surface to the bedrock surface, which directly influences the vulnerability of the main useful aquifer.	5
Hydraulic conductivity (C)	Represents the ability of the aquifer to transmit water and the rate at which a contaminant moves in an aquifer. Higher hydraulic conductivity is associated with a higher contamination risk.	3

The modified DRASTIC method was used to calculate the vulnerability to pollution of the first bedrock (main useful) aquifer in the Estonian-Latvian TBA. The ranges and ratings used for each parameter are shown in Table 13. The data sources for the parameters are given in Table 14.

Table 34. Parameters and ratings used to calculate groundwater vulnerability of the main useful aquifer

(D) Depth to water		(R) Net recharge		(A) Aquifer media		(S) Quaternary sediment type	
Depth of the piezometric head compared to the bedrock surface (m)*	Rating	Range (mm/y)	Rating	Type	Rating	Type	Rating
<-10	10	0–50	1	Devonian Aruküla-Amata aquifer system; sandstone with siltstone interlayers	6	Clay	1
-10…-5	9	50–100	3	Devonian Plavinas-Ogre aquifer system; dolomite with dolomitic marl	10	Bedrock	2

(D) Depth to water		(R) Net recharge		(A) Aquifer media		(S) Quaternary sediment type	
-5…-1	7	100–175	6			Peat	6
-1…0	6	175–250	8			Gravel	6
0…1	5	> 250	9			Sand	7
1…3	3					Till	8
3…5	2						
>5	1						
(T) Topography		**(I) Thickness of the Quaternary sediments**		**(C) Hydraulic conductivity**			
Slope (%)	Rating	Range (m)	Rating	Range (m/d)		Rating	
0–2	10	0–2	10	0,04–4		1	
2–6	9	2–5	9	4–12		2	
6–12	5	5–10	7	12–28		4	
12–18	3	10–20	5	28–40		6	
>18	1	20–40	3	40–80		8	
		>40	1	>80		10	

* negative values indicate a piezometric head below the bedrock surface

Table 35. Data sources for the DRASTIC parameters

Parameter	Data source	Data format
D	Estonian-Latvian transboundary area hydrogeological model	Raster data
R	Estonian-Latvian transboundary area hydrogeological model	Raster data
A	MapPortal EE-LV pilot area - Hydrogeological units of the MUA layer	Vector data, 1:200 000
S	Generalized EE-LV Quaternary sediments map	Vector data, 1:200 000
T	Digital elevation model from Lidar elevation data	Raster data
I	Estonian-Latvian transboundary area hydrogeological model	Vector data, 1:200 000
C	Estonian-Latvian transboundary area hydrogeological model	Vector data, 1:200 000

In the modified method, the depth to water (D) parameter is used to compare the piezometric head of the first bedrock aquifer to the bedrock surface (Figure 27). When the piezometric head is above the bedrock surface, the aquifer acts as confined, and the movement of the pollutant to the aquifer is hindered. Therefore, the vulnerability of the aquifer is higher in areas where the piezometric head is above the bedrock surface and lower in areas where it is below the bedrock surface. The piezometric surface of the first bedrock aquifer from the EE-LV hydrogeological model and the bedrock surface were used to calculate the D-parameter. A lower vulnerability rating indicates a higher water table and lower risk to pollution. Areas with a rating 1 cover 98,7% of the TBA, rating 2 – 0,6%, rating 3 – 0,3%, rating 5 – 0,1%, rating 6 – 0,1%, rating 7 – 0,2 % and rating 9 cover 0,03% of the TBA.

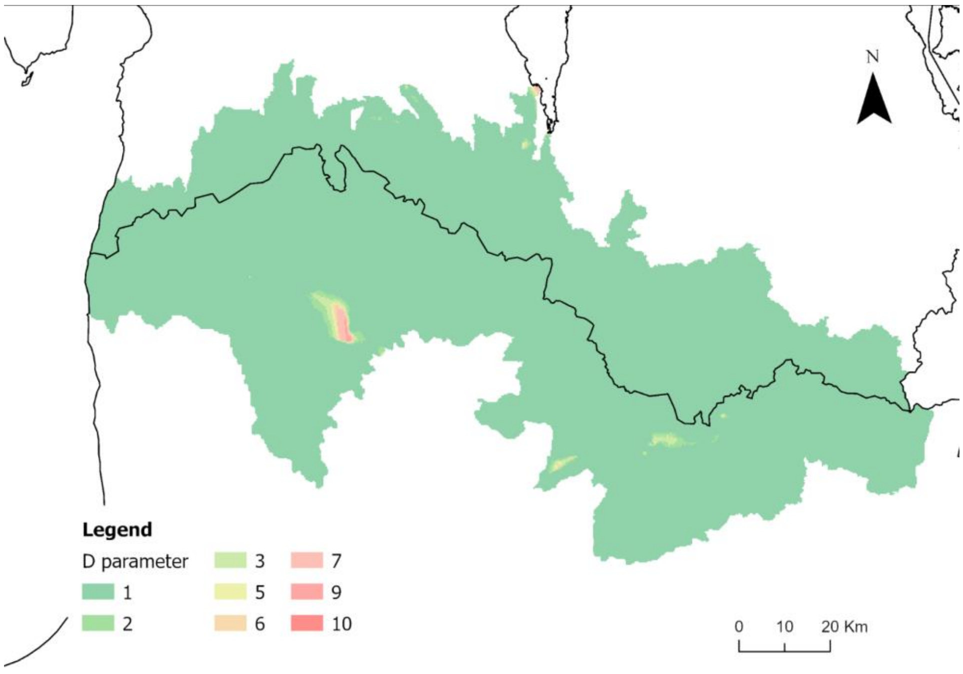


Figure 47. Depth to water (D) parameter ratings in the Estonian-Latvian TBA.

To assess the net recharge (R) parameter, net recharge data from the EE-LV hydrogeological model were used (see Figure 21 in chapter 3.1.2)

The aquifer media (A) parameter describes the properties of the rock forming the first bedrock aquifer, such as lithology, texture and structure. The main useful aquifer layer from the EE-LV MapPortal and information about the aquifer properties were used for the A-parameter (Figure 28). Aquifer type with a higher pollution risk receives a higher vulnerability rating. Areas with a rating 6 cover 79,1% and rating 10 cover 20,9% of the TBA.

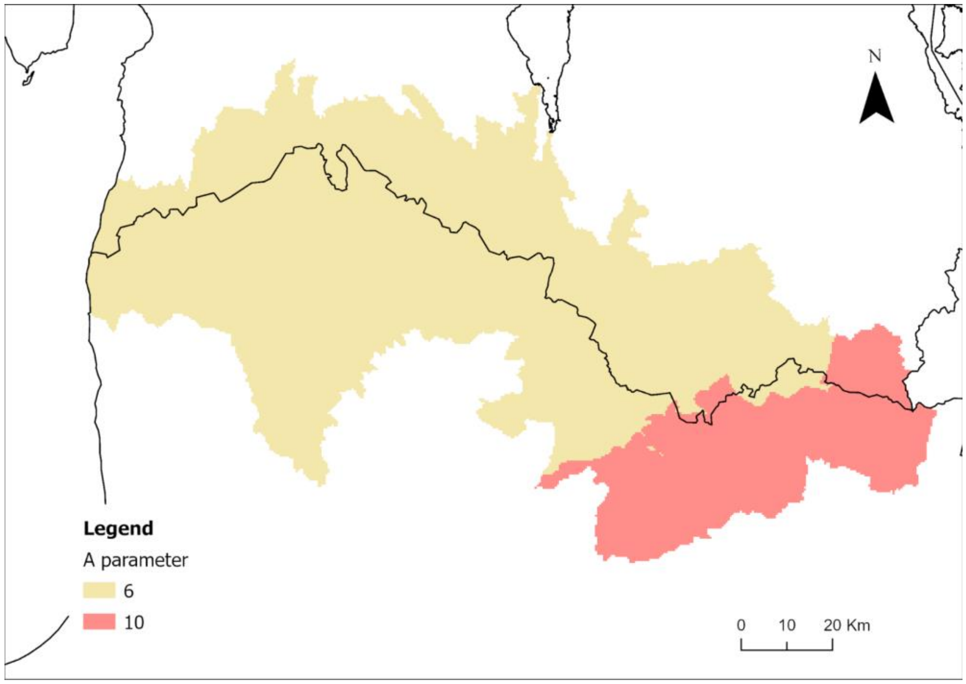


Figure 48. Aquifer media (A) parameter ratings on the Estonian-Latvian TBA.

Considering the importance of the Quaternary sediment types to the vulnerability of the main useful aquifer and their correlation with soil types, the soil type (S) parameter was replaced by the Quaternary sediment type parameter to assess the geological characteristics of the deposits. For the analysis of the S-parameter, the generalized Quaternary map of the transboundary area was used (see Figure 23 in chapter 3.1.2).

For the topography (T) parameter, a digital elevation model from Lidar elevation data was used to assess the impact of slopes on the pollution potential (see Figure 24 in chapter 3.1.2).

The vadose zone (I) parameter is used to assess the impact of the unsaturated zone above the water table. However, the vadose zone for the main useful aquifer is formed by the Quaternary deposits and the properties of the sediments and their impact on the vulnerability were described in the Quaternary sediment type (S) parameter. Therefore, the parameter was replaced by the thickness of the Quaternary sediments parameter to describe the path of the pollutant from the ground surface to the main useful aquifer (Figure 29). Areas with thick Quaternary sediments layer will receive a lower vulnerability rating. Areas with a rating 1 cover 27,8% of the TBA, rating 3 – 53,5%, rating 5 – 15,5%, rating 7 – 2,5%, rating 9 – 0,5% and rating 10 cover 0,2% of the TBA.

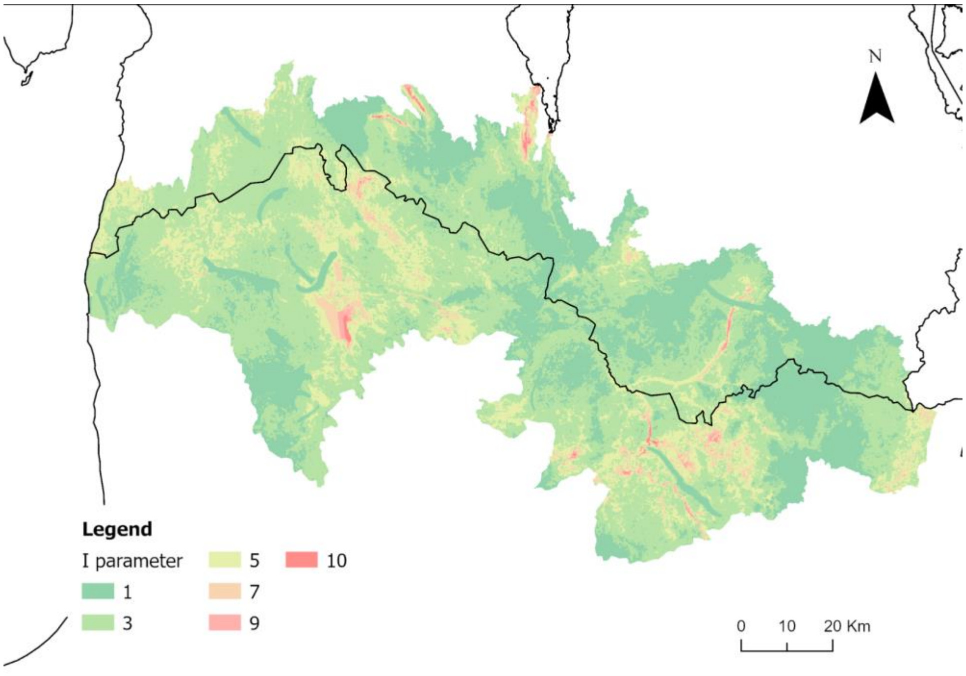


Figure 49. Thickness of the Quaternary (I) parameter ratings on the Estonian-Latvian TBA.

For the hydraulic conductivity (C) parameter, values from the EE-LV hydrogeological model were used to assess the impact of the aquifer's hydraulic conductivity on the pollution potential (Figure 30). A higher hydraulic conductivity value receives a higher vulnerability rating. Areas with a rating 1 cover 92,2% of the TBA, rating 2 – 3,4%, rating 4 – 0,2%, rating 6 – 0,1% and rating 8 cover 4,1% of the TBA.

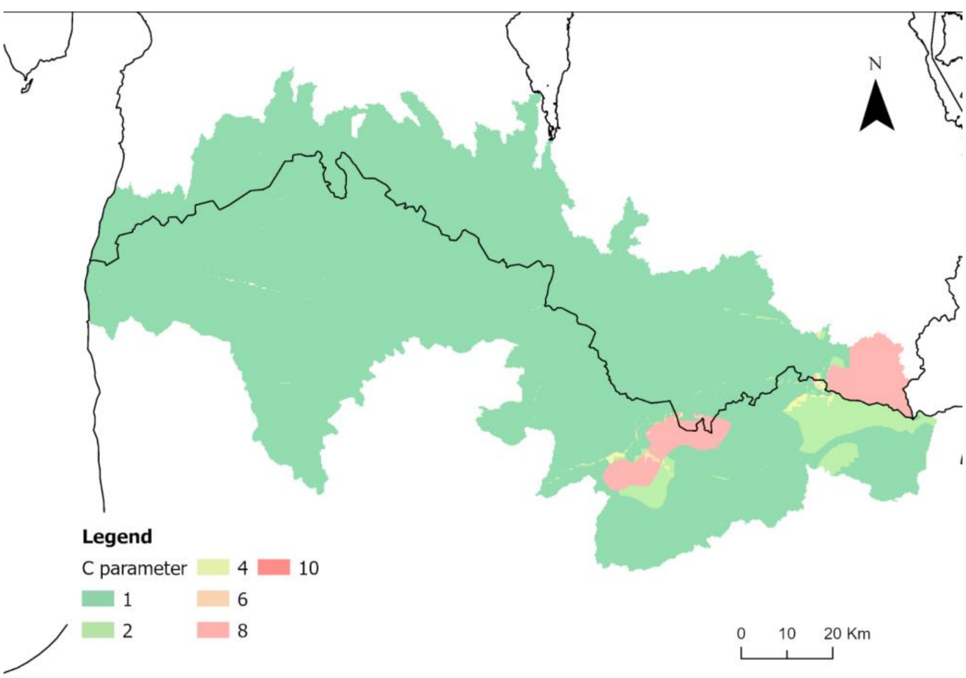


Figure 50. Hydraulic conductivity (C) parameter ratings on the Estonian-Latvian TBA.

3.2 Vulnerability maps in the Estonian-Latvian transboundary area

3.2.1 Groundwater vulnerability map of the Quaternary aquifer (DRASTIC method)

The DRASTIC method was used to calculate the vulnerability to pollution of the Quaternary aquifer in the Estonian-Latvian TBA. The final vulnerability index values of the map ranged from 54-164. The values were divided into five classes (Table 15) according to the percentage range suggested by Hamza et al. (2015).

Table 36. Vulnerability index (Di) values divided into five vulnerability classes

	Percentage of the Di range	Di values
Well protected	10-28,99	85,89
Relatively well protected	29-46,99	105,69
Moderately protected	47-64,99	125,49
Weakly protected	65-82,99	145,29
Unprotected	83-100	164,00

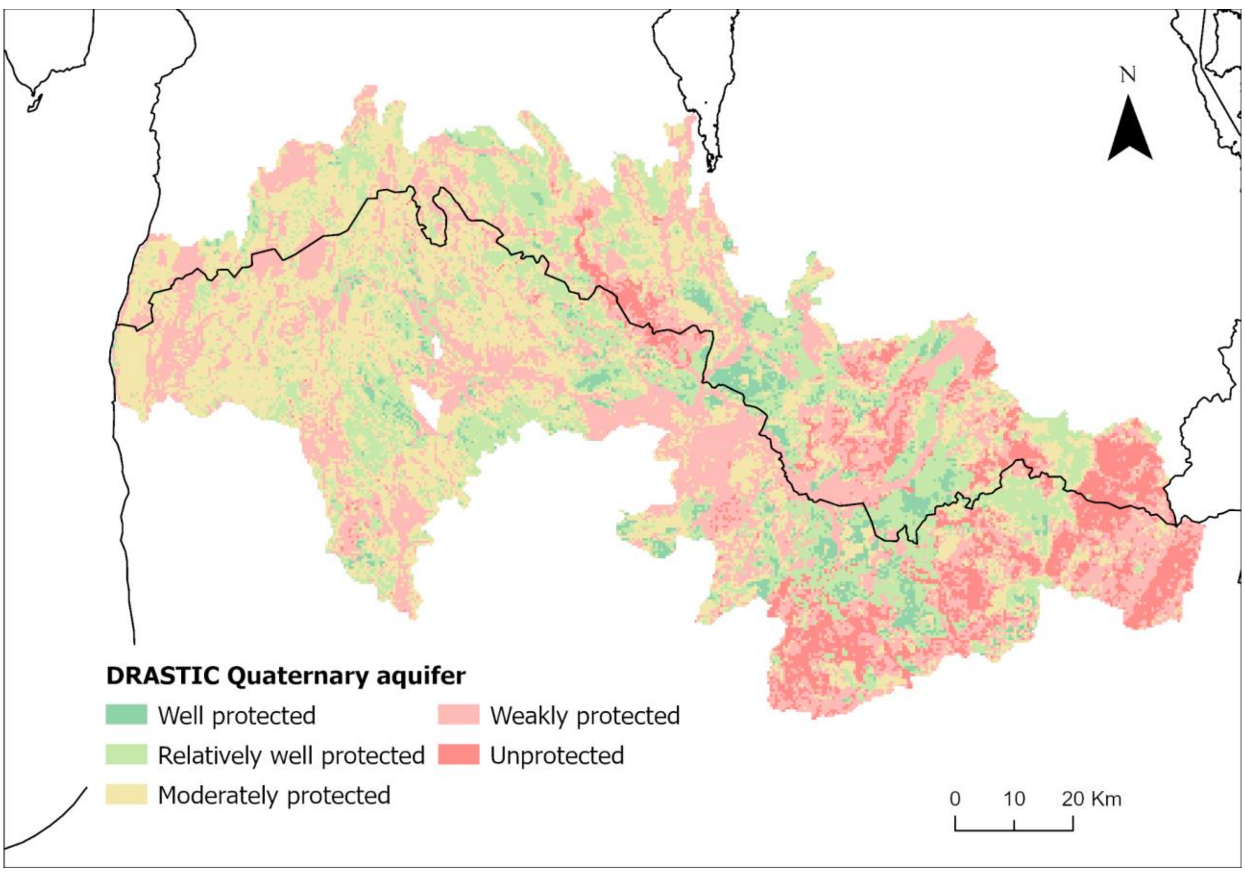


Figure 51. Groundwater vulnerability map of the Quaternary aquifer in the Estonian-Latvian TBA

In the Quaternary vulnerability map, protected areas covered 4,3% of the TBA. These regions are characterized by clay and have a deeper groundwater level. Relatively protected areas occupy 21,3% of the TBA and consist predominantly of till and have a deeper groundwater level. Areas, which are covered with till, but have a shallower groundwater level, form moderately protected areas, covering 33,1% of the TBA. Weakly protected areas form 32,1% of the TBA and primarily coincide mostly with areas covered with sands as well as peatlands. Sands with a shallower groundwater level are classified as unprotected areas, covering 9,1% of the TBA.

3.2.2 Groundwater vulnerability map of the main useful aquifer (modified DRASTIC method)

The DRASTIC method was used to calculate the vulnerability to pollution of the main useful aquifer in the Estonian-Latvian TBA. The final vulnerability index values of the map ranged from 45-181. The values were divided into five classes (Table 16) according to the percentage range suggested by Hamza et al. (2015).

Table 37. Vulnerability index (Di) values divided into five vulnerability classes

	Percantage of the Di range	Di values
Well protected	10-28,99	84,4
Relatively well protected	29-46,99	108,9
Moderately protected	47-64,99	133,4
Weakly protected	65-82,99	157,9
Unprotected	83-100	181

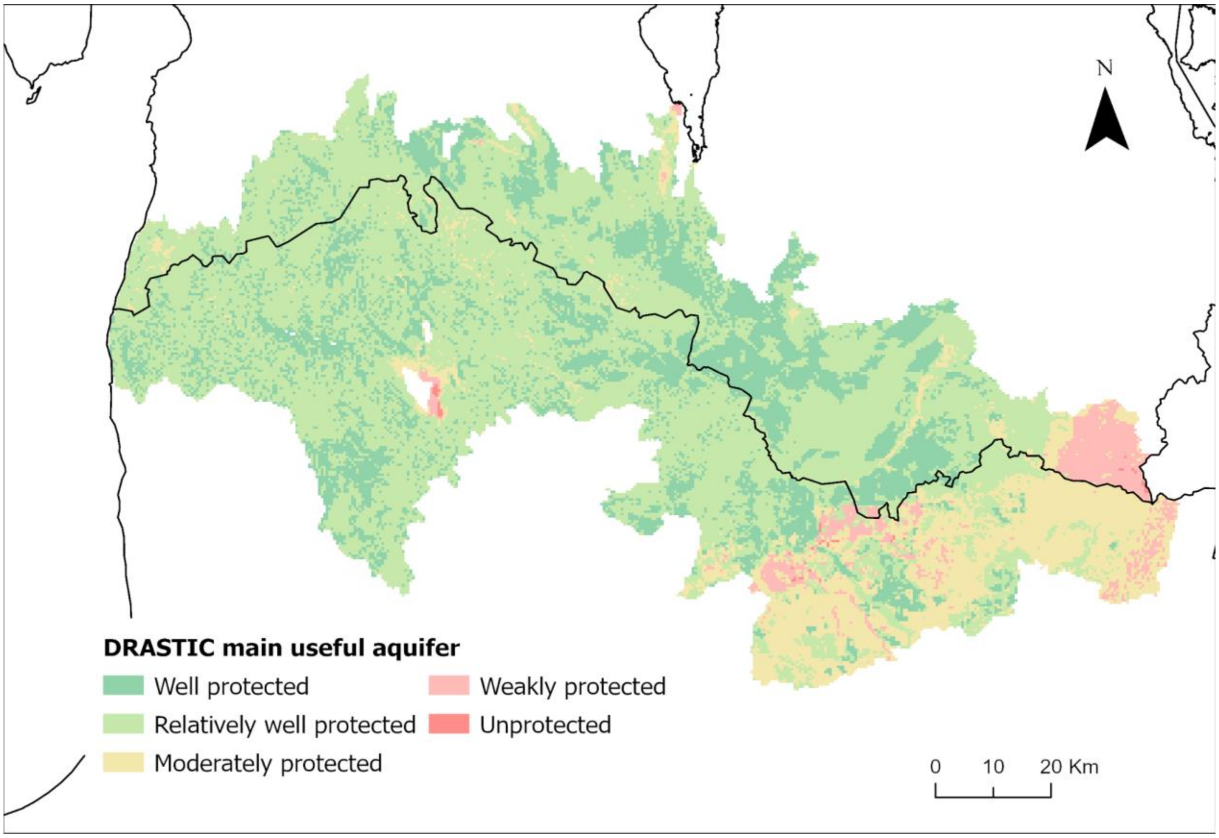


Figure 52. Groundwater vulnerability map of the main useful aquifer in the Estonian-Latvian TBA

In the groundwater vulnerability map of the most useful (first bedrock) aquifer, protected areas cover 23% of the TBA. These areas coincide mostly with the Aruküla-Amata sandstone aquifer, which serves as the first bedrock aquifer. Furthermore, within these protected areas, the Quaternary sedimentary cover above the aquifer is characterized by substantial thickness and/or the presence of clay layers. Conversely, in regions where the Quaternary cover is comparatively thinner, relatively protected areas are formed, covering 59,1% of the TBA.

Moderately protected areas coincide mostly with the Plavinas-Ogre aquifer, which serves as the first bedrock aquifer composed of fissured dolomites and limestones. These areas have a thinner layer of Quaternary sediment, and they cover 14% of the TBA. Weakly protected areas represent 3,7% of the TBA, mostly in the areas of Plavinas-Ogre aquifer, where the Quaternary cover predominantly consists of sand. In instances where the Quaternary cover is thin, the areas are unprotected, however, they occur only in 0,1% of the TBA.

3.2.3 Groundwater vulnerability map for the unsaturated zone (Vertical infiltration time calculation method)

The application of the Macioszczyk equation to the EE-LV transboundary with three hydraulic conductivity sets of values (min, max and median) yielded three vulnerability maps for the unsaturated zone of the EE-LV transboundary area. The most representative vulnerability map of the vertical travel time approach is the map with the lowest hydraulic conductivity values (Figure 34) where realistic hydraulic conducivities for vertical flow was were used. Typically hydraulic conductivity in vertical direction is ~10 times lower than in horizontal axis which is approximately in line with the lowest k values used in the map (Figure 34; Table 8). The map (Figure 34) indicates that 40% of the EE_LV transbonundary area is considered as very highly vulnerable and 23% as highly vulnerable for the unsaturated zone implying that unsaturated zone can be easily polluted in large parts of the territory. These are typically territories with thin unsaturated zone and Quaternary deposits with relatively high hydraulic conductivities. Average vulnerability accounts for 12% of the area, low vulnerability for 13% and very low vulnerability is covered by 12% of the transboundary territory, thus there are still relatively large parts where pollution on the ground surface do not pose a risk for the shallow groundwater just beneath the unsaturated zone.

It must be noted that the approach yielded also vulnerability maps with estimated median and high values of hydraulic conductivities which results in lower protection estimates for the EE-LV transboundary area for unsaturated zone, but these maps should not be considered as realistic and rather as a demonstration of uncertainty with changes in values of hydraulic conductivities (Figures 33, 35).

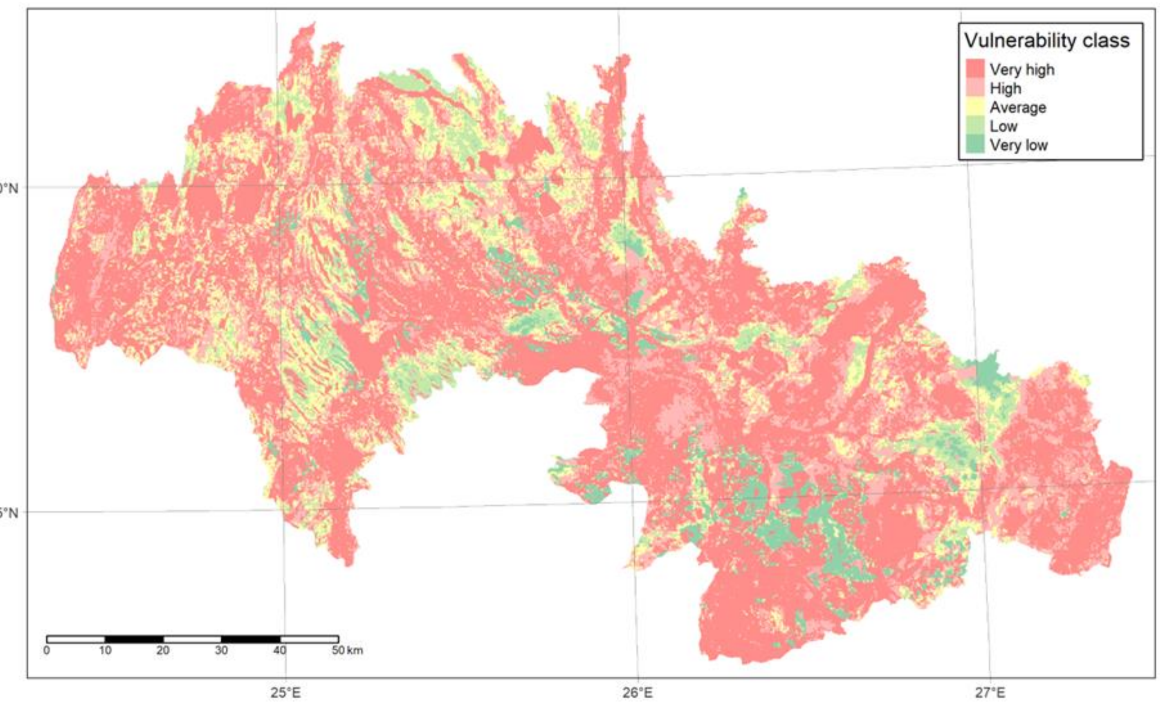


Figure 53. Vulnerability map for the unsaturated zone of EE-LV transboundary area (using optimum values of hydraulic conductivity)

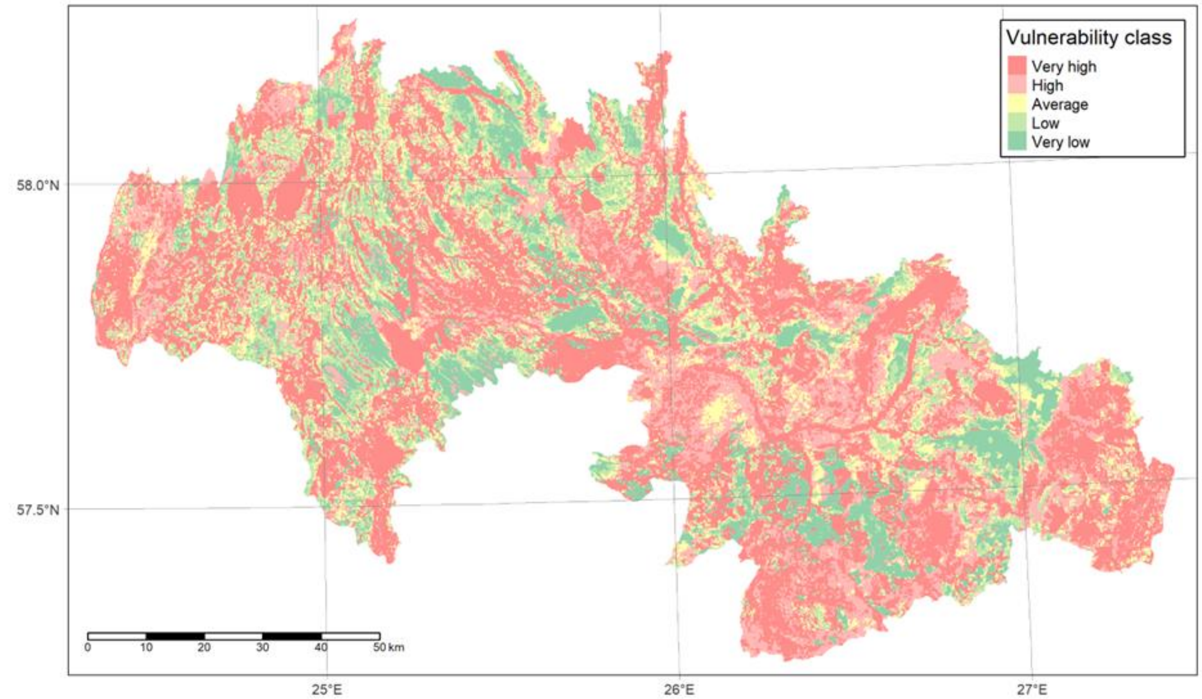


Figure 54. Vulnerability map for the unsaturated zone of EE-LV transboundary area (using lowest values of hydraulic conductivity)

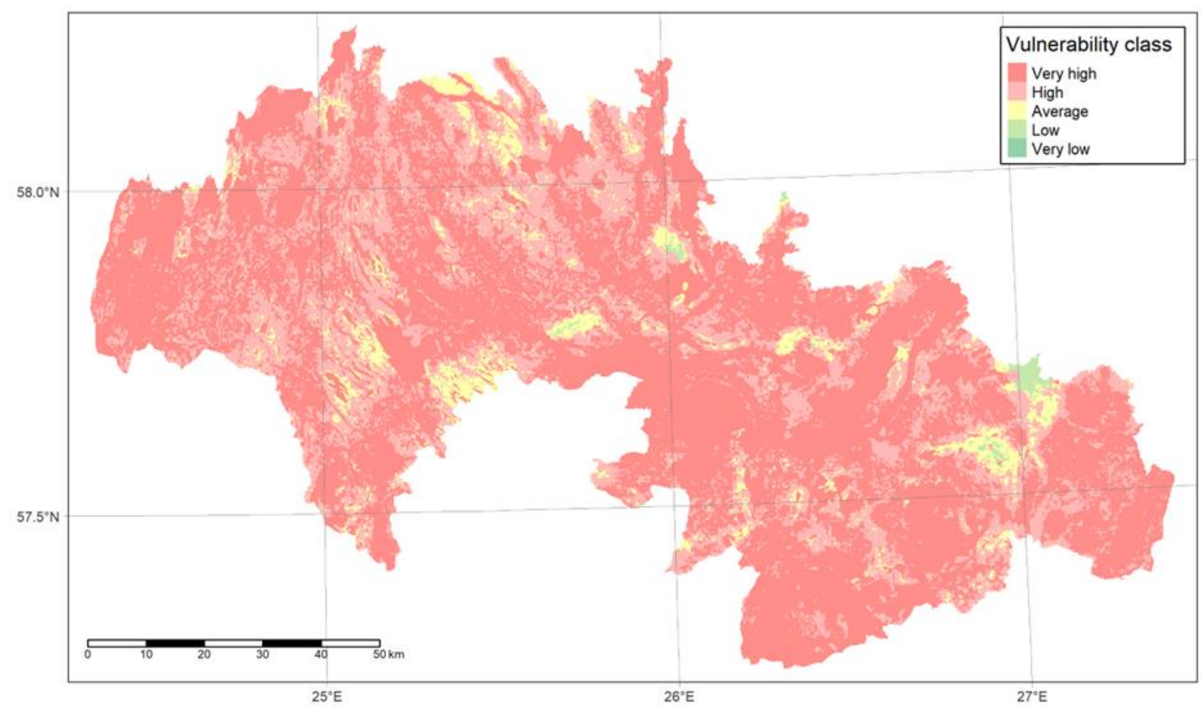


Figure 55. Vulnerability map for the unsaturated zone of EE-LV transboundary area (using highest values of hydraulic conductivity)

3.3. Comparison of methods (Vertical infiltration time calculation, DRASTIC)

Two different groundwater vulnerability assessment methods were used to assess the vulnerability of the Quaternary aquifer in the Estonian-Latvian transboundary area: the DRASTIC method and the Macioszczyk method for vertical infiltration time calculation. While both methods evaluate the vulnerability, they differ in their approach and parameters used.

The DRASTIC method is an overlay-index approach that combines several maps containing specific parameter data to determine the overall vulnerability of an aquifer. It considers parameters such as depth to water, net recharge, aquifer and soil media, topography, impact of the vadose zone, and hydraulic conductivity. Each parameter is assigned a rating based on its vulnerability. On the other hand, the Macioszczyk method calculates the time of the pollutant to reach the aquifer though the unsaturated zone, focusing on parameters directly related to pollutant travel time. These parameters include the thickness of the unsaturated zone, average moisture content, infiltration intensity, and vertical hydraulic conductivity.

The groundwater vulnerability maps generated using the DRASTIC and Macioszczyk methods are both classified into five classes according to their vulnerability degree. For some parameters in both methods, same datasets were used, such as the generalized hydrogeological map, similar hydraulic conductivity values, and outcomes from the EE-LV hydrogeological model. Therefore, there are a lot of similarities between the two methods, particularly in the areas categorized as highly protected or highly vulnerable. For example, clayey areas are identified as protected, while sandy areas tend to be identified as more vulnerable. However, in the medium vulnerability zones, which include areas classified as medium protected, relatively well protected, and weakly protected, differences are more evident. The variations in the results are due to the distinct approaches and different parameters considered by each method.

The Macioszczyk method offers a higher level of objectivity due to its reliance on concrete parameter values and calculations. The use of measurable values for each parameter allows a more precise estimation of pollutant travel time. On the other hand, the DRASTIC method offers greater adaptability by allowing for modifications to consider additional factors, such as land use, to assess diffuse pressure. This flexibility makes the DRASTIC method more suitable for further pollution risk assessment, considering the significance of land use as a potential pressure on groundwater quality. Additionally, it was possible to assess the vulnerability of the main useful (first bedrock) aquifer using a modification of the DRASTIC which takes into account the specific properties of the overlining Quaternary sediments.

4. Assessment of the transboundary pressures on groundwater

4.1. Diffuse pollution

4.1.1 Methodology

For the impact of diffuse pressure assessment, a modified version of the DRASTIC method was used. By adding the land use parameter to the DRASTIC model, a DRASTIC-L model is created (Wang et al. 2022, Goodarzi et al. 2022, Zhang et al. 2022, Rauf et al. 2022, Wel et al. 2021). The new L-parameter receives a rating of 5. In the DRASTIC-L method, the vulnerability index (Di) is calculated with the following equation:

$$Di = D_wD_r + R_wR_r + A_wA_r + S_wS_r + T_wT_r + I_wI_r + C_wC_r + L_wL_r,$$

where *w* – weight of parameter, *j* – rating of parameter.

To assess the land use (L) parameter in the EE-LV TBA, Corine Land cover data was used (Corine Land Cover, 2018) and land cover types received a rating according to the rating scales by previous authors (Table 17). Land cover types and ratings used are given in Table 18.

Table 38. Land use types and their L-parameter ratings in modified DRASTIC models by different authors

Wang et al. 2022		**Goodarzi 2022**		**Zhang 2022**		**Wel 2021**		**Rauf 2022**	
Type	Rating	Type	Rating	Type	Rating	Type	Rating	Type	Rating
Industrial district	10	River bed	1	Unused land	2	Agricultural area	9	Vegetation and barren land	5
City proper	7	Forest and shrubland	2	Grassland	3	Water body	8	Rivers and lakes	7
Cultivated land	4	grassland	3	Forest	4	Built-up area	6	Cultivated land	8
Forestland	2	Residential areas	7	Waters	5	Land for transportation	4	Rural and agriculture	8
Water body	1	Agriculture	8	Dry land	6	Tree-clad area	3	Rural and industrial	9
		Garden	9	Paddy field	7			Urban and industrial	10
				Rural land	8				
				Urban land	9				
				Industrial land	10				

Table 39. Land use types from the Corine Land Cover database and their ratings in the DRASTIC-L model

Corine land use type	L parameter rating
Artificial surfaces	10
Agricultural areas	8
Forest and semi natural areas	2
Wetlands	1
Water bodies	1

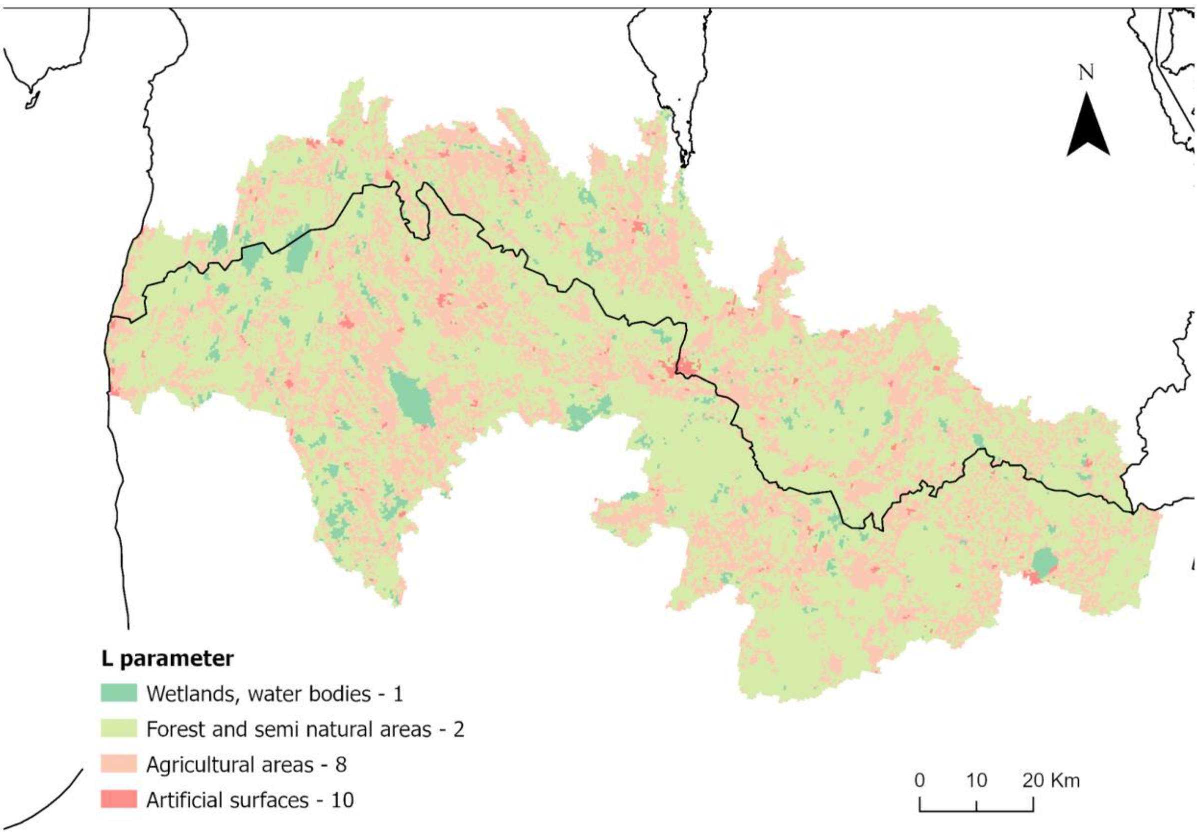


Figure 56. Land use parameter ratings in the Estonian-Latvian transboundary area.

4.1.2 Results

The DRASTIC-L method was used to calculate the pollution risk of the Quaternary aquifer in the Estonian-Latvian TBA. The final vulnerability index values of the map ranged from 54-214. Additionally, the DRASTIC-L method was used to calculate the pollution risk of the main useful aquifer, resulting in vulnerability index values ranging from 58-227. The values were divided into five classes (Table 19) according to the percentage range suggested by Hamza et al. (2015). The classes represent the pollution risk of the aquifers based on the natural vulnerability combined with the land use types in the Estonian-Latvian TBA.

Table 40. Vulnerability index (Di) values divided into five vulnerability classes

	Percentage of the Di range	Di values DRASTIC-L Quaternary	Di values DRASTIC-L main useful aquifer
Well protected	10-28,99	100,4	107,0
Relatively well protected	29-46,99	129,2	137,4
Moderately protected	47-64,99	158,0	167,8
Weakly protected	65-82,99	186,8	198,3
Unprotected	83-100	214,0	227,0

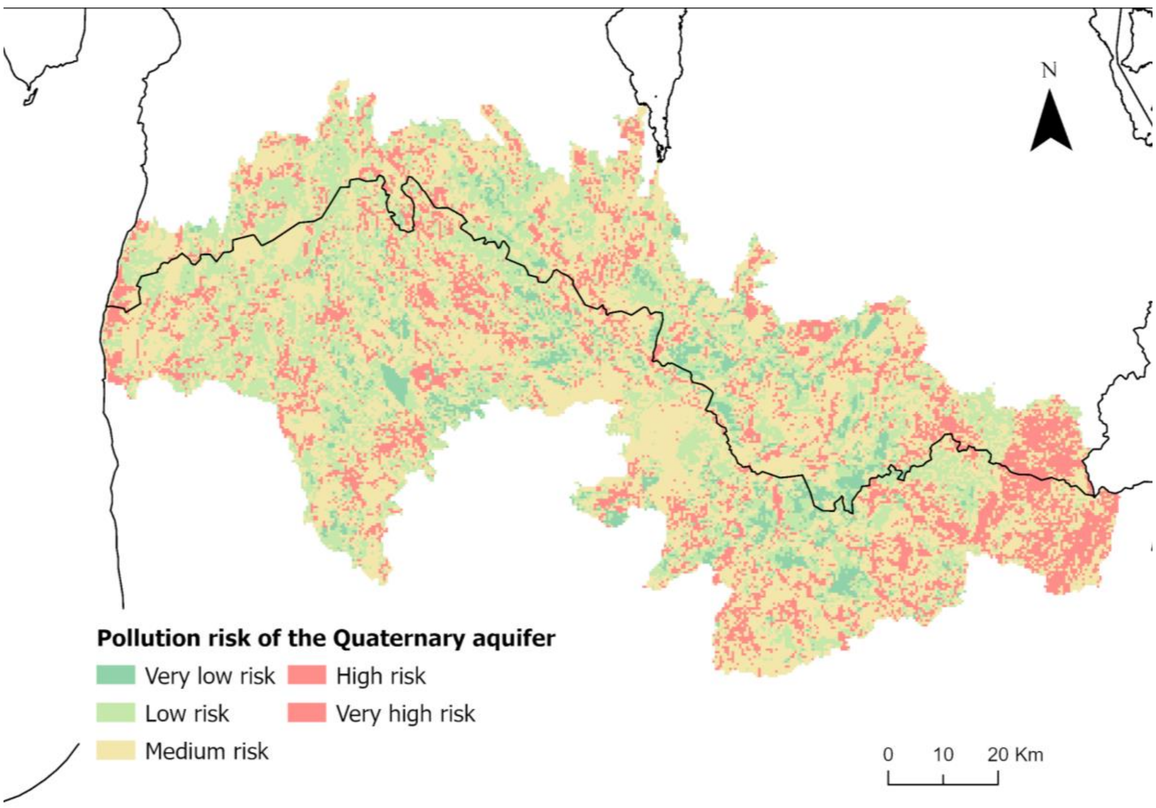


Figure 57. Diffuse pressure analysis of the Quaternary aquifer using the DRASTIC-L method

Within the study area, approximately 5.6% is classified as a very low risk to pollution. These areas are primarily characterized by forested land cover, which contributes to their natural protection. Additionally, these areas are naturally either well protected or relatively well protected, further reducing the vulnerability of the Quaternary aquifer to potential contamination. The low-risk category represents approximately 26.4% of the study area. Wetlands and forested areas are the main land use types within this classification, contributing to the lower vulnerability of the Quaternary aquifer

The medium risk area covers approximately 47.4% of the study area. Within this category, areas are naturally either moderately or relatively well protected, however, agricultural land increases the pollution risk. Additionally, these areas represent naturally weakly protected areas where the pollution risk is significantly lower due to the occurrence of forested and semi-natural areas.

Approximately 18.7% of the study area falls into the high-risk category. This includes areas where land use is predominantly agriculture or areas that remain naturally unprotected, including forested regions. A small portion, accounting for 1.9% of the study area, is categorized as a very high-risk area. These areas are characterized by being both unprotected and primarily used for agricultural purposes. Furthermore, the presence of artificial surfaces increases the vulnerability of the Quaternary aquifer within these regions.

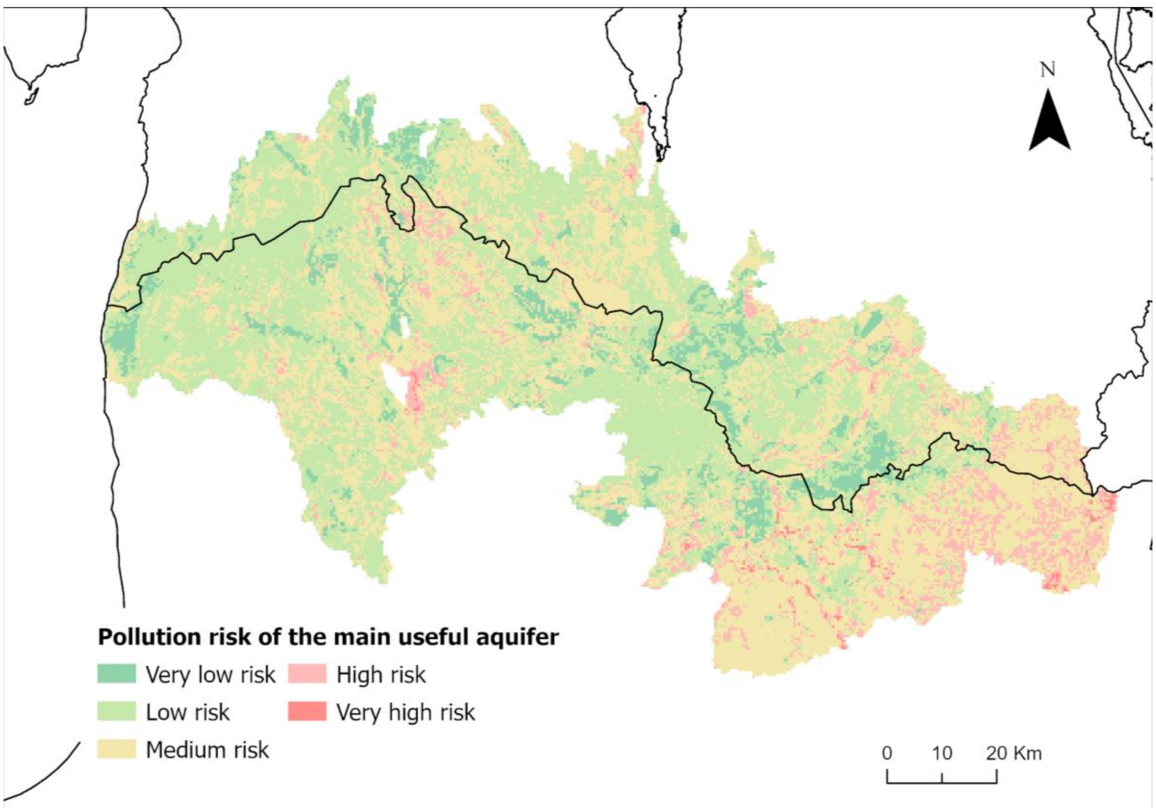


Figure 58. Diffuse pressure analysis of the main useful aquifer using the DRASTIC-L method

According to the results of the pollution risk analysis of the main useful aquifer, approximately 7,2% is classified as a very low-risk area. This category coincides with the Dar-am aquifer, characterized by naturally well protected or relatively well protected areas. Notably, forested and semi-natural areas contribute significantly to the protection of this aquifer, minimizing the potential risk of contamination.

Within the study area, the low-risk category represents 43,2% of the study area. Here, the Dar-am aquifer remains relatively well protected, and the pollution risk is low due to the presence of forested and semi-natural areas, as well as wetlands.

The medium pollution risk area covers approximately 41.3% of the study area. Within this category, the Dar-am aquifer is naturally relatively well protected. The presence of agricultural areas leads to a moderate level of pollution risk. While agricultural practices can contribute to potential contamination, the existing level of protection helps mitigate risks to some extent. The higher vulnerability of the Dpl-og aquifer leads to a medium risk of pollution in forest and semi-natural areas.

Approximately 7.9% of the study area falls into the high pollution risk category. This includes moderately protected areas within the Dar-am aquifer, where the presence of agricultural activities increases the vulnerability to potential contamination. Additionally, the Dpl-og aquifer is also exposed to higher risks due to agricultural land use. High pollution risk is also characterized in the areas of artificial surfaces. A small portion, 0.4% of the study area, is categorized as having a very high risk of pollution. These areas are naturally weakly protected or unprotected, primarily consisting of agricultural land.

4.2. Point source pollution

17 polluted and potentially polluted places in the Latvian-Estonian border territory were initially identified for point pressure assessment. In order to assess the potential impact of sites on groundwater, the path of pollution particle flows for a 30-year period was modeled for each identified site.

4.2.1 Methodology

This chapter presents the methodology employed in this report for the analysis of particle movement in groundwater flow simulations using MODPATH (Pollock, 2016). MODPATH is a 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. MODPATH serves as a valuable tool for analyzing the movement of particles in groundwater systems and is widely utilized in hydrogeological and environmental studies.

The study utilized MODFLOW-NTW, which is based on a three-dimensional network of rectangular grid cells known as a structured grid. Each cell in the grid is connected to neighboring cells or system boundaries through six faces. This grid representation provides the spatial framework for particle tracking. To determine the groundwater velocity distribution required for particle tracking, the flow rates across each cell face were computed. These flow rate components represent the inflow and outflow across the faces of the grid cells (Q_x, Q_y, Q_z) and serve as input for the subsequent particle tracking process.

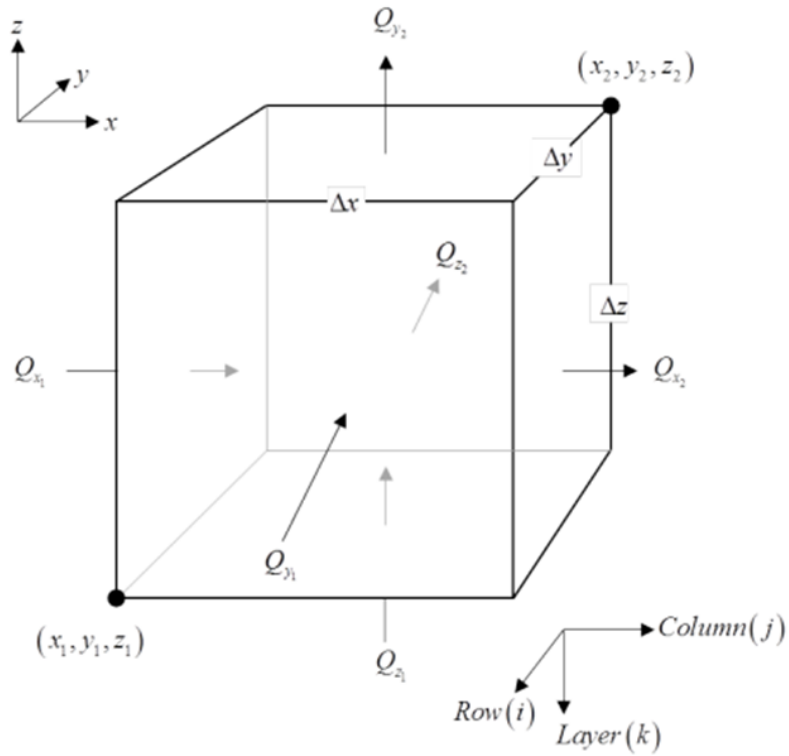


Figure 59. A schematic of a cell showing volumetric flow components (Pollock, 2016)

Velocity components at various points within the flow system were interpolated from the velocity components at the cell faces. The average linear velocity component across each face of a cell was calculated by dividing the volumetric flow rate by the face's cross-sectional area and the porosity of the material within the cell (eq. 5.1). Linear interpolation was then used to estimate the velocity components within each cell based on the values at the cell faces (eq. 5.2).

$$\boldsymbol{v_{x_1}} = \frac{\boldsymbol{Q_{x_1}}}{\boldsymbol{n\Delta y\Delta z}}, \qquad \boldsymbol{v_{x_2}} = \frac{\boldsymbol{Q_{x_2}}}{\boldsymbol{n\Delta y\Delta z}} \tag{5.1}$$

$$v_x = A_x(x - x_1) + v_{x_1} \tag{5.2}$$

, where x, y, z are coordinates, n is porosity, v is volumetric flow rate, Q is inflow and outflow across its cell faces, A is velocity gradient within the cell (see how components are defined across cell faces from fig. X). Analogous equations can be developed for the y and z coordinates of the particle.

The direct integration method was employed to determine the time and location at which a particle exits a cell (eq. 5.3). Given a known starting location within a cell, an algorithm was used to identify the potential exit faces for the particle. The exit time and coordinates were computed based on these potential exit faces, allowing for the tracking of particle movement within the grid system.

$$x_t = x_1 + \frac{1}{A_x}\left[(v_x)_{t_1} e^{A_x(t-t_1)} - v_{x_1}\right] \tag{5.3}$$

, where x, y, z are coordinates, v is volumetric flow rate, A is velocity gradient within the cell, and t is time. Analogous equations can be developed for the y and z coordinates of the particle.

Particle tracking was conducted through a cell-by-cell approach, applying the algorithm described above iteratively. The calculations were performed from one cell to another until a termination condition was met or the particle reached a cell with no potential exit face (Figure 40A). This method allowed for the comprehensive tracking of particles as they moved throughout the flow system.

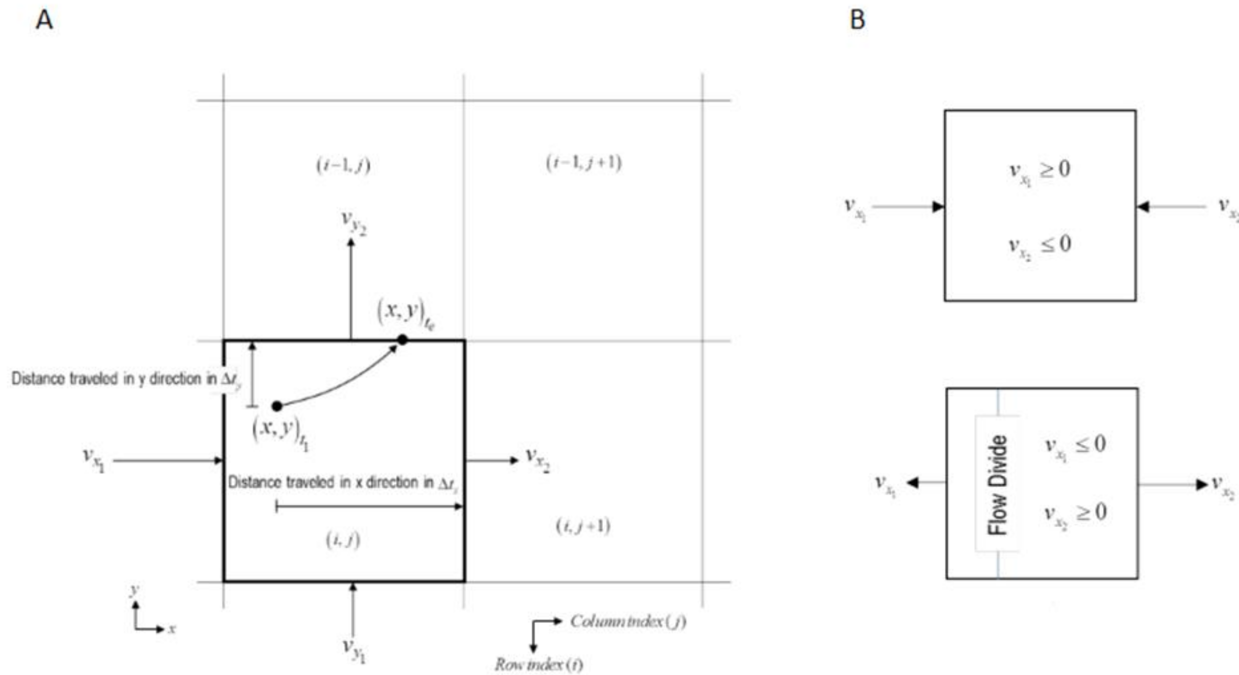


Figure 60. A- Two-dimensional flow diagram showing the computation of exit point and travel time. B- Combinations of velocities (v) between pairs of cell faces (Pollock, 2016)

The particle tracking algorithm accounted for different flow conditions within the grid system. Situations where particles could not exit a cell in a specific direction or where flow divides occurred within a cell were taken into consideration (Figure 40B). Special calculations and considerations were applied to address these varying flow conditions.

The methodology outlined in this chapter provided a structured approach to tracking particle movement in groundwater flow simulations using MODPATH. By employing a structured grid representation, calculating flow rates, interpolating velocity components, utilizing the direct integration method, performing cell-by-cell calculations, and accounting for different flow conditions, the analysis of particle paths within the flow system was facilitated. The subsequent sections of this report will present the results and interpretation of the particle tracking analysis.

As part of this report, flow paths were calculated for all point sources of pollution mentioned in chapter xx using the hydrogeological model described in report xx. The flow paths were calculated for a 30-year period and with the assumption that the pollution has reached the surface of the Quaternary aquifer. To calculate the flow rates, 5x5 particles were placed in each cell that overlapped with the point source pollution object. Particles were placed on the top face of the cell and pathlines were generated by forward tracking.

To validate model results length of pathlines were also calculated using simple groundwater velocity (particle velocity) formula:

$$V_{gw} = K \times L/n \quad (5.4)$$

, where Vgw is groundwater velocity, K is horizontal conductivity, L is horizontal hydraulic gradient, and n is effective porosity.

Groundwater velocity refers to the rate at which water flows through the subsurface. Multiplying groundwater velocity by the time for which we want to calculate the length of the flow path, we get the flow path length of the particle for the given time, in this case for 30 years. Used horizontal conductivity, hydraulic gradient, and porosity were taken from the model.

4.2.2 Results

Figure 41 illustrates 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. More detailed images of the potential impact zones for each site are attached in the Annex I.

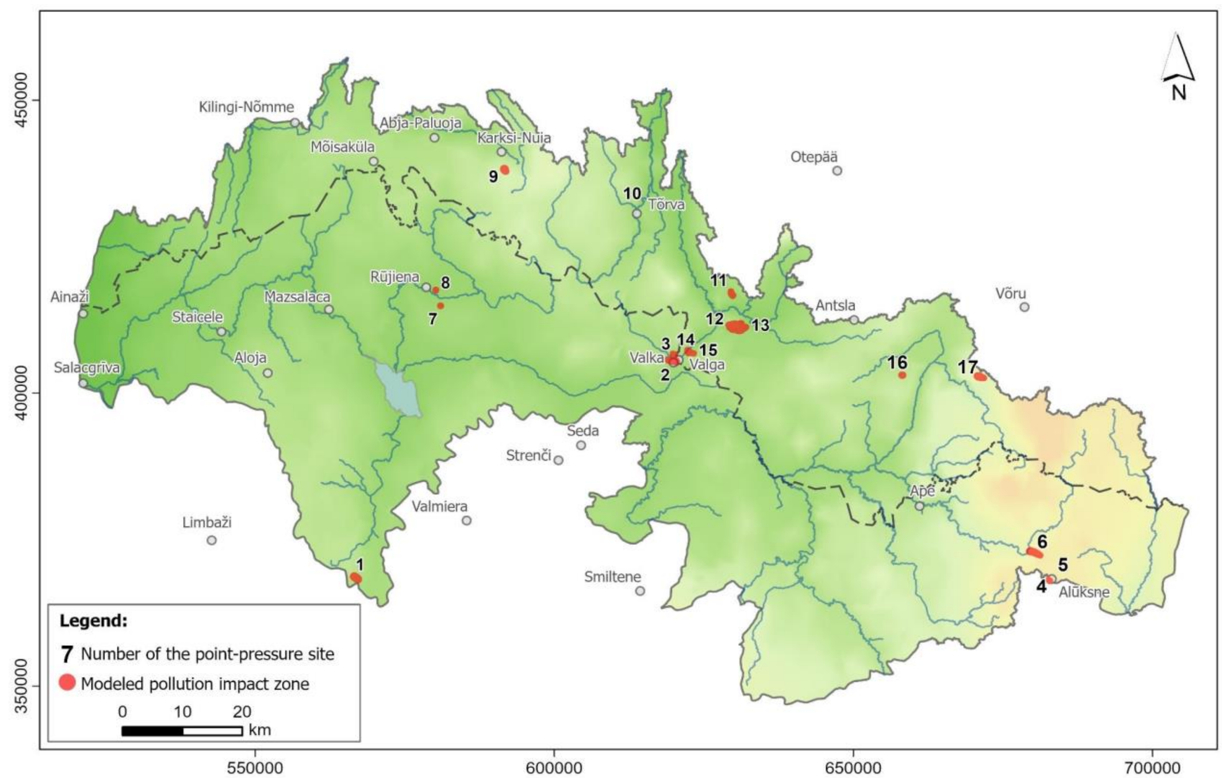


Figure 61. Potential impact zones of identified point-pressure sites in Latvian-Estonian study area

Most of the pathlines observed in the model are contained within one or two model cells, with each cell having a size of 250m. The Valga/Valka area exhibits the longest pathlines due to the presence of a higher hydraulic gradient. This increased gradient is a result of greater water consumption in that specific area and the proximity to a nearby river.

Table 20 presents the information on the calculated potential impact zones of the identified point-pressure sites in Latvian-Estonian study area. The results of the model calculations were studied in more detail for each site, as a result of which the table gives a general description of the potential impact on the surrounding environment and evaluates whether the potential impact of the specific site would be significant or insignificant.

Table 20 also shows a comparison between the flow path lengths calculated by the model and those determined using the groundwater velocity formula. In general, the error between the two methods is confined to a single grid cell, except for three points. The Valga bitumen base, Pollution on Rūjiena street 5, and Alūksnes putnu fabrika" display errors of 900 m, 540 m, and 1064 m, respectively. It is worth noting that when examining the model results for the first two points, the pathline reaches the Pedele river. The disparity arises from the consideration of boundary conditions, such as the river boundary, in the model, which is not accounted for in the groundwater velocity formula.

In general, it can be concluded that potentially significant impacts are mostly caused by objects located in the territory of settlements and cities. In the transboundary area, the largest pressure is concentrated in the cities of Valka/Valga, which are located right on the Latvian-Estonian borderline. There are four contaminated sites that may pose a potential threat to groundwater quality and surrounding environment (e.g. "Tīne" LLC gas station and oil base; Pollution on Rūjiena street 5, Valka; Valga bitumen base and Priimetsa asphalt concrete factory) and model results shows that in some sites the potential contamination flow could cross the boundary in over a longer period of time. 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.

Table 41. Characterization of potential impact zone of identified point-pressure sites

No	Name	K, m/d	L	n	Length (calculated), m	Length (model output), m	Difference, m	Zone area, ha	Description of potential impact zone	Significance of potential impact
1.	Solid waste landfill "Daibe"	5	0.0007	0.25	143.08	287.73	144.65	54	The modeled particle flow is directed towards the south-east. In the potential impact zone, besides the territory of the landfill itself, forest areas are mainly distributed.	Not significant
2.	"Tīne" LLC gas station and oil base	5	0.006	0.25	1192.33	1384.77	192.44	28	Station is located in Valka city, approximately 1450 m from the Latvian-Estonian border. The particle movement flow is eastward, towards the border. The construction of the city of Valka (residential and public buildings) is located in the potential impact zone. According to the model results, in a longer time period (> 30 years) the flow possibly could cross the Latvian-Estonian border.	Significant
3.	Pollution on Rujiena street 5, Valka	5	0.005	0.25	1077.75	538.67	-539.07	7	The facility is located in Valka city, approximately 700 m from the Latvian-Estonian border. The potential impact zone is directed in the south-east direction. The construction of the city of Valka (residential and public buildings) is located in the potential impact zone.	Significant
4.	State JSC "LATVIJAS AUTOCEĻU UZTURĒTĀJS" gas station	5	0.001	0.25	251.08	160	-91.08	8	Potential impact zone is oriented towards the north-west. Since the gas station is located in the territory of the Alūksne city, there are residential houses and public buildings in the potential impact zone.	Significant
5.	SW bay of Alūksne lake	-	-	-	-	-	-	-	Considering that the contaminated site is located in a lake (pollution in sediments), it is not possible to calculate the particle flow with the hydrogeological model in this particular case	n/a
6.	"Alūksnes putnu fabrika" LLC ("VISTAKO" LLC), poultry farm	5	0.004	0.25	717.57	1781.83	1064.26	87	The main flow is directed in the north-west direction. In this area, the Quaternary layer consists mainly of sand and gravel deposits, so the affected area is relatively large and the modeled	Not significant

No	Name	K, m/d	L	n	Length (calculated), m	Length (model output), m	Difference, m	Zone area, ha	Description of potential impact zone	Significance of potential impact
									overflow distance could reach about 2000 m. Mostly forests and clearings are distributed in the affected area. Closer to the poultry farm are two households. Since pollution has not been detected in this place, the operation of the poultry farm in the current situation does not pose a threat to the surrounding environment.	
7.	"KUNTURI" LLC, pig farm	5	0.0009	0.25	175.20	57.82	-117.38	1	The modeled potential impact zone is local. Mainly it includes the territory of the farm itself and some agricultural land and forest areas adjacent to it.	Not significant
8.	"EAST-WEST TRANSIT" LLC gas station "RŪJIENA"	5	0.0001	0.25	13.63	73.23	59.60	1	The main flow is directed towards the south-east. The gas station is located near a residential area and there are households in the potential impact zone. Taking into account that groundwater pollution has already been detected here, it can be assumed that this gas filling station has a significant impact	Significant
9.	Äriküla fertilizer-poison storage	5	0.003	0.25	537.28	654.53	117.25	23	The flow is directed in the north-west direction. The potential impact zone is mainly spread over agricultural lands, as well as two households located in this zone. Since the pollution is already almost eliminated, it can be assumed that there is no significant potential impact.	Not significant
10.	Härma asphalt concrete factory	5	0.00	0.25	0.00	0.00	0.00	-	It is not possible to calculate pathlines in the model because the object is located in depression. No pollution has been detected in the area, so it can be assumed that this site does not have a significant potential impact on the surrounding environment.	Not significant
11.	Tsirguliina asphalt concrete factory	5	0.003	0.25	616.44	778.36	161.92	38	The flow is directed mainly to the south. The potential impact zone is mostly agricultural land. Modeling results show that the flow could reach the former quarry water area. Since the pollution	Not significant

No	Name	K, m/d	L	n	Length (calculated), m	Length (model output), m	Difference, m	Zone area, ha	Description of potential impact zone	Significance of potential impact
									is already almost eliminated, it can be assumed that there is no significant potential impact.	
12.	Vilaski rocket base town and car base	5	0.004	0.25	749.47	584.27	-165.20	119	Potential impact zone is directed in a wider area, in the direction of the south-west. Since the former rocket base is located further from populated areas, the area of influence is mainly forested.	Not significant
13.	Vilaski rocket installation area and nuclear warhead warehouse	5	0.006	0.25	1135.21	1305.35	170.14	133	Potential impact zone is directed in a wider area, in the direction of the south-east. Since the former rocket base is located further from populated areas, the area of influence is mainly forested.	Not significant
14.	Valga bitumen base	5	0.009	0.25	1839.60	907.00	-932.60	11	This base is located in the suburbs of Valga city. Potential impact zone is directed north-west towards the Pedele river, which flows through the Valka/Valga border cities.	Significant
15.	Priimetsa asphalt concrete factory	5	0.005	0.25	1022.00	1150.33	128.33	39	This factory is located in the suburbs of Valga city. The flow is directed towards the north (away from the city). Potential impact zone extends beyond the inhabited area, including forest areas, meadows and transport infrastructure.	Not significant
16.	Tsooru collective farm oil storage	5	0.001	0.25	185.82	259.16	73.34	5	The flow is directed towards the east. Calculated potential impact zone is relatively local and it covers mainly the village territory. Some residential houses of the village are located in the potential impact zone.	Significant
17.	Rõuge toxic chemical warehouse	5	0.006	0.25	1133.49	1122.20	-11.29	56	The flow is directed in the north-west direction. Potential impact zone is covered by forests and agricultural lands. There are also two households about 1 km away.	Not significant

4.2.3. Groundwater abstraction pressure

For groundwater abstraction pressure assessment, a regional-scale hydrodynamical hydrogeological model was used, which was developed in EU-WATERRES project and was created specially to assess the water level changes of the groundwater aquifers in the Estonian-Latvian transboundary area. Hydrogeological model was developed using open-source software MODFLOW-NWT and aggregated geological, hydrogeological data on the research area. More detailed information about the model (model structure, grid, boundary and other) is available in the EU-WATERRES project report on WP5 "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 nearby the area of the operating dolomite quarry "Ape", with current pumping rate up to 4274 m^3/d. Accordingly, in the Quaternary (Q) and Upper-Devonian (Pļaviņas-Ogre) aquifer systems groundwater level is more than 2 m lower in the dolomite quarry "Ape" area (Figure 42). On the other hand, lowering of the groundwater levels of the Upper-Middle-Devonian (Aruküla-Amata) aquifer system due to current groundwater abstraction has not been identified.

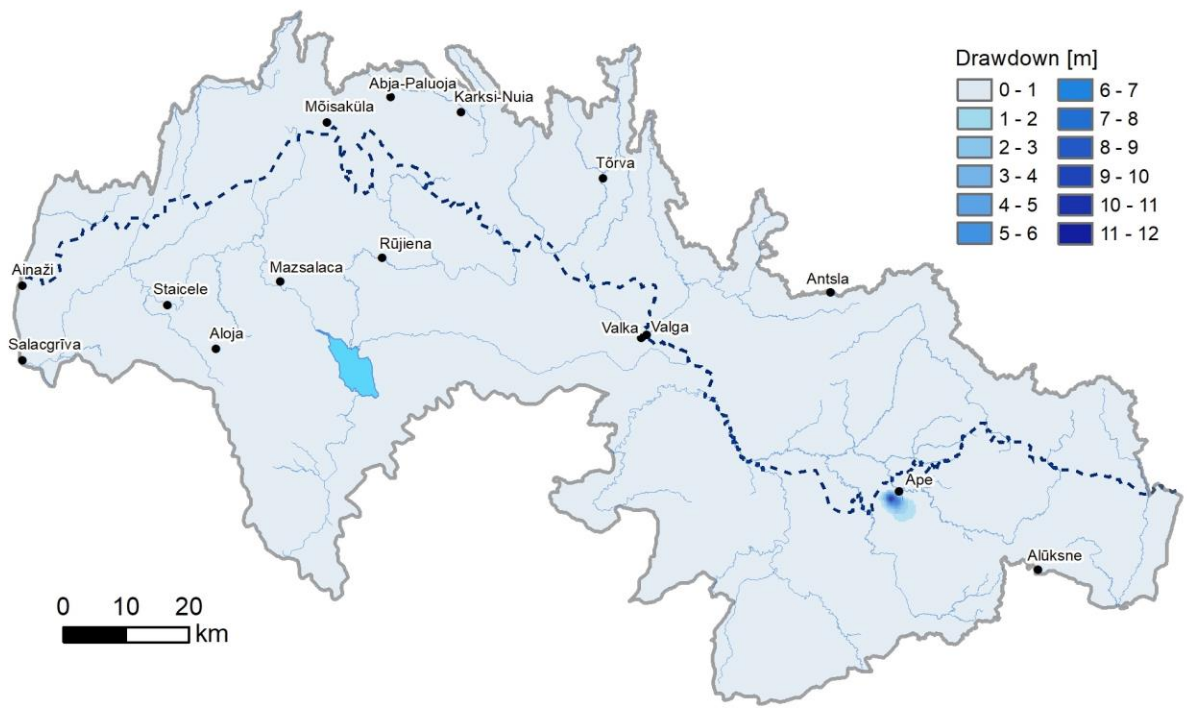


Figure 62. Simulated groundwater drawdown with current exploitation rate from 2012–2021 (represents all three aquifer systems)

The calculated groundwater balance shows 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 (8100 m^3/d) make up 0.01% from the natural renewable groundwater resources (16.8*10^5 m^3/d). 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 21.

Table 42. Water budget of the Estonia-Latvia TBA in the current exploitation model (*10^5 m^3/d)

		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	-

*changes compared to the natural state

Taking into account that in the existing groundwater well fields (in Latvia - abstraction over 100 m^3/d, in Estonia - abstraction over 500 m^3/d) the current groundwater abstraction does not reach a maximum of the accepted groundwater exploitation reserves, a second simulation was performed. The conducted simulation reflected increased groundwater abstraction in all groundwater well fields up to the maximum permissible volumes (35 835 m^3/d), as well as additional potential dolomite quarries ("Dārzciems -2" on the Latvia side and two potential dolomite quarries on the Estonian side - “Kalkahju” and "Naha"), in which groundwater levels are lowered, and it was also assumed that the existing dolomite quarry "Ape" will be fully developed at the maximum water pumping volume - 10 170 m3/d. A simulation of groundwater abstraction showed that increased groundwater abstraction results in larger depression cones and a uniform drawdown over a wider area. The biggest drawdown in groundwater levels remained at 13 m in the Upper-Devonian (Pļaviņas-Ogre) and Quaternary (Q) aquifer systems near the quarries, and around the quarries in a wider area, a drawdown up to 2 m is formed. In Latvia, around the Alūksne city in the Upper-Devonian (Pļaviņas-Ogre) aquifer, a slight decrease up to 1-2 m is formed, which is mainly related to the increased abstraction in the groundwater well field "Alūksne" - 2 149 m^3/d.

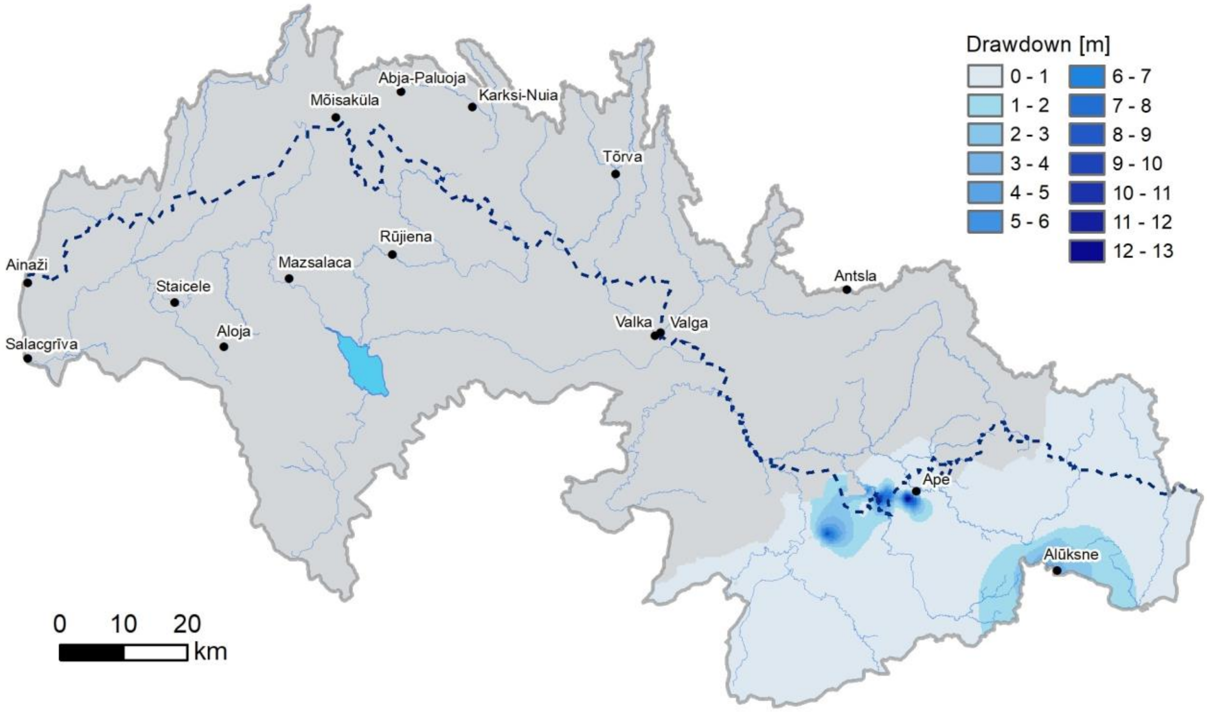


Figure 63. Groundwater drawdown in Upper-Devonian (Pļaviņas-Ogre) aquifer with increased abstraction volumes

On the other hand, in Upper-Middle-Devonian (Aruküla-Amata) aquifer system (mainly in its lower part), in the eastern part of the TBA, the widest depression is formed up to 2-3 m, which is related to groundwater abstraction outside of the TBA. Drawdown is caused from the low filtration coefficient of the aquifer in areas where the aquifer is covered with the Plavinas-Ogre aquifer system, and from higher water abstraction is larger cities (from outside the pilot area). And only locally, in the territory of Latvia, drawdown reaches 12 m, which is connected with maximum allowed abstraction in the city of Cesis and Valmiera (Figure 44). Despite the identified drawdowns, it can be concluded that increased groundwater abstraction does not significantly affect the hydrodynamic conditions of the Upper-Middle-Devonian (Aruküla-Amata) aquifer system and does not affect groundwater resources. Increased groundwater abstraction (32 096 m^3/d) makes up 1% from the natural renewable groundwater resources ($15*10^5$ m^3/d).

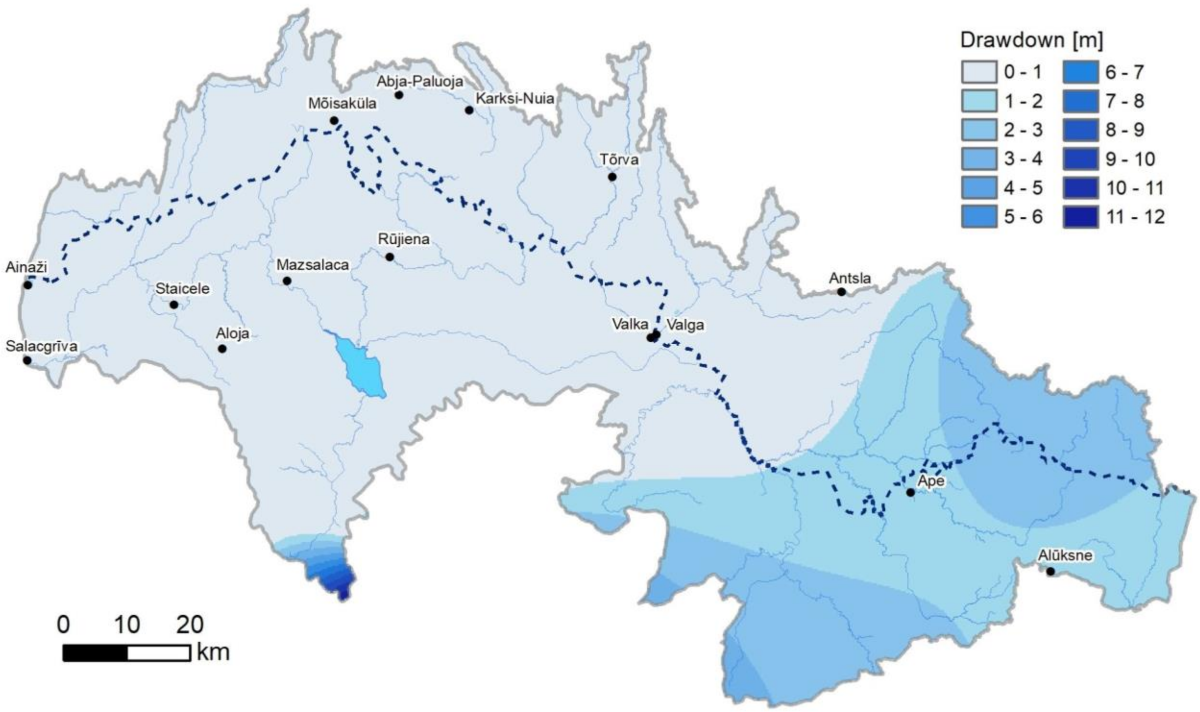


Figure 64. Groundwater drawdown in Upper-Middle-Devonian (Aruküla-Amata) aquifer with increased abstraction volumes

In balance terms, changes in the TBA's system under the influence of increased groundwater exploitation for the analyzed variant have been presented in Table 22, but the groundwater natural resources of the TBA are collected in Table 23.

Table 43. Water budget of Estonia-Latvia TBA in the exploitation model (*10^5 m^3/d)

		Latvia, 10^5 m^3/d	Latvia*, %	Estonia, 10^5 m^3/d	Estonia*, %
Inflow	Surface water infiltration	62.64	0.0	41.21	↓2.4
	Rainwater infiltration	19.83	0.0	13.63	0.0
	Groundwater inflow from outside the model area	0.87	0.0	2.62	↑0.4
	Inflow from deeper aquifer	9.59	0.0	9.40	↓0.1
Outflow	Discharge to streams (river)	70.51	0.0	49.87	↓2.0
	Discharge to lakes	0.00	0.0	0.00	0.0
	Discharge to Baltic Sea	1.10	0.0	0.27	0.0
	Evapotranspiration	cannot be calculated with the model			
	Pumping amount from wells	0.07	-	0.26	-
	Groundwater outflow to outside the model area	1.24	0.0	1.11	↓43.7
	Outflow to deeper aquifer	10.94	0.0	5.42	0.0
	Amount going out to storage (Up)	7.58	↓15.6	8.01	↓0.9

		Latvia, 10^5 m^3/d	Latvia*, %	Estonia, 10^5 m^3/d	Estonia*, %
	Transboundary flow (inflow)	+1.06	↑14.0	+1.5	↑16.3
	Transboundary flow (outflow)	-1.4	↑8.5	-1.13	↑21.5
	Total Inflow	92.93	0.0	66.86	↓1.5
	Total Outflow	93.83	↑1.1	67.31	↑1.1
	Error, %	-0.00001	-	-0.00001	-

*changes compared to the natural state

Table 44. Natural groundwater resources, m^3/d

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

5. Summary of anthropogenic impact assessment

In order to assess the anthropogenic impact on transboundary groundwater, first, the information on anthropogenic pressure (diffuse, point and water extraction) in the Latvian-Estonian transboundary area was collected and assessed its impact on common groundwater resources.

Vulnerability maps were developed for both shallow Quaternary aquifer and MUA (D_3ar-am and D_3pl-og aquifer systems), with the aim of identifying the natural protection of groundwater in the transboundary area. These maps showed that in the study area the bedrock aquifers (D_3pl-og, $D_{2\text{-}3}$ar-am aquifer systems, which are mainly used for water supply, are better protected from pollution compared to the shallower Quaternary aquifer. Accordingly, they are less affected by diffuse as well as point pressure.

Finally, for the assessment of the impact of anthropogenic pressure on groundwater, pollution risk maps were developed (for both Quaternary and MUA), combining vulnerability maps with identified pressures.

According the results, the impact of anthropogenic pressure (diffuse and point pressure) on MUA is insignificant, because only 8.3% of the study 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_3pl-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 study area is at high or very high pollution risk) and the impact of anthropogenic pressure.

Groundwater abstraction pressure was assessed using the developed hydrogeological model for the transboundary area. The results of the model calculations confirmed that the natural resources of groundwater are significantly greater than water abstraction, so it can be considered that anthropogenic influence does not have a significant impact on the groundwater resources. However, in order to continuously assess the situation of groundwater resources, this developed hydrogeological model must be updated and supplemented with newer data.

Overall, it was concluded that no anthropogenic pressure has been identified in the considered area, which can significantly affect the quality of groundwater and make significant changes in the state of groundwater resources, i.e. to change the hydrodynamic conditions in the Latvian-Estonian transboundary area. Despite this, it is still necessary to continue close cooperation between countries in order to sustainably and effectively manage common groundwater resources in the transboundary area in the future. In order to improve the current assessment of the impact of anthropogenic pressure, it is necessary to carry out a number of measures: update and improve the developed hydrogeological model; review anthropogenic pressures by gather new data on agricultural activity and creating a unified database on identified risk objects; focus more on those areas where the greatest risk of pollution has been identified and where there is a greater overflow of groundwater between the state borders (e.g. Valka-Valga border cities, the area of the Gauja-Koiva river basins).

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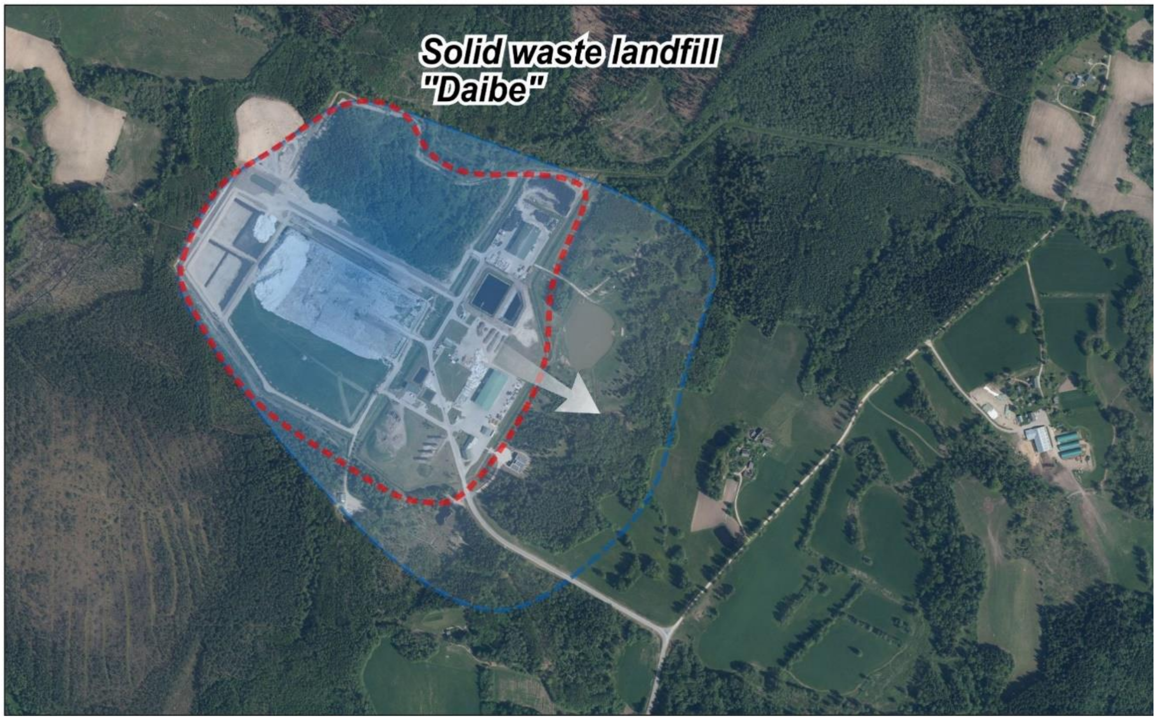
Annex I. **Modeled potential impact zones for the identified point-pressure sites in Latvian-Estonian study area**

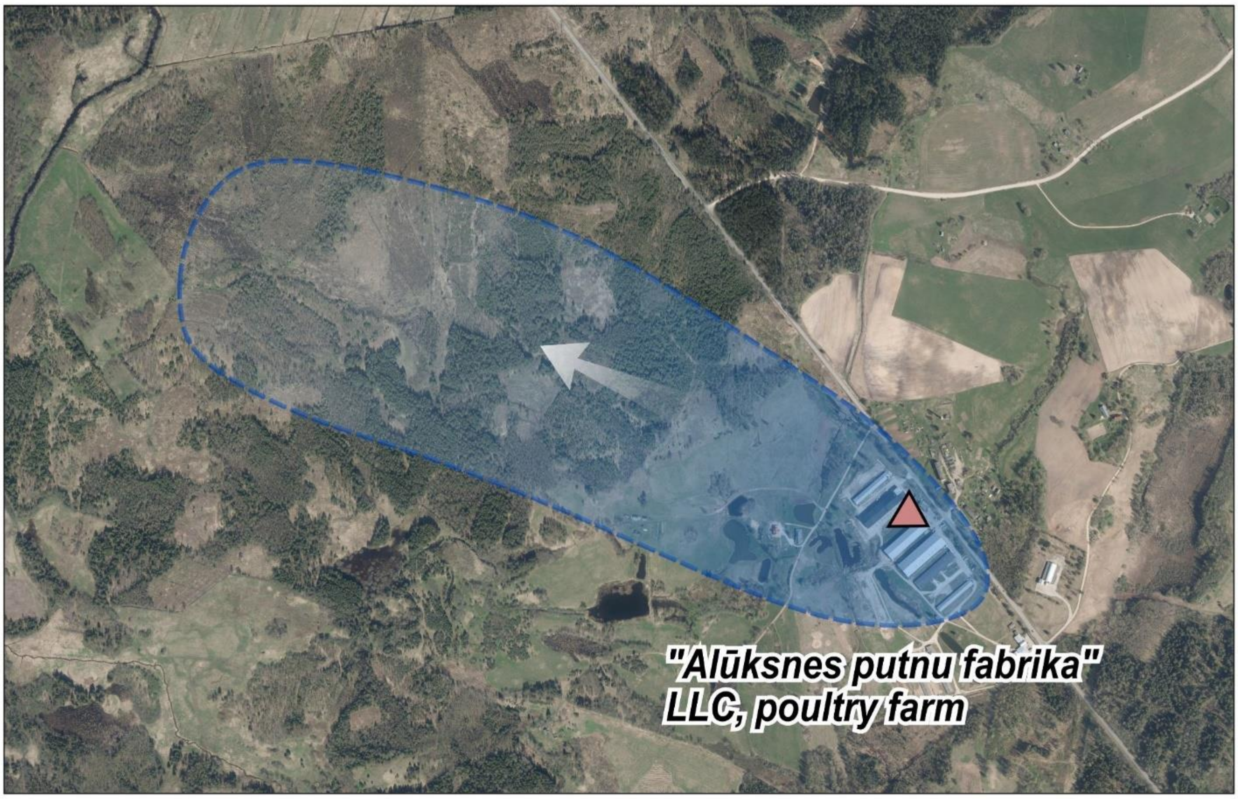
1.Solid waste landfill “Daibe”



2.,3. "Tīne" LLC gas station and oil base & Pollution on Rujiena street 5, Valka

4. State JSC "LATVIJAS AUTOCEĻU UZTURĒTĀJS" gas station

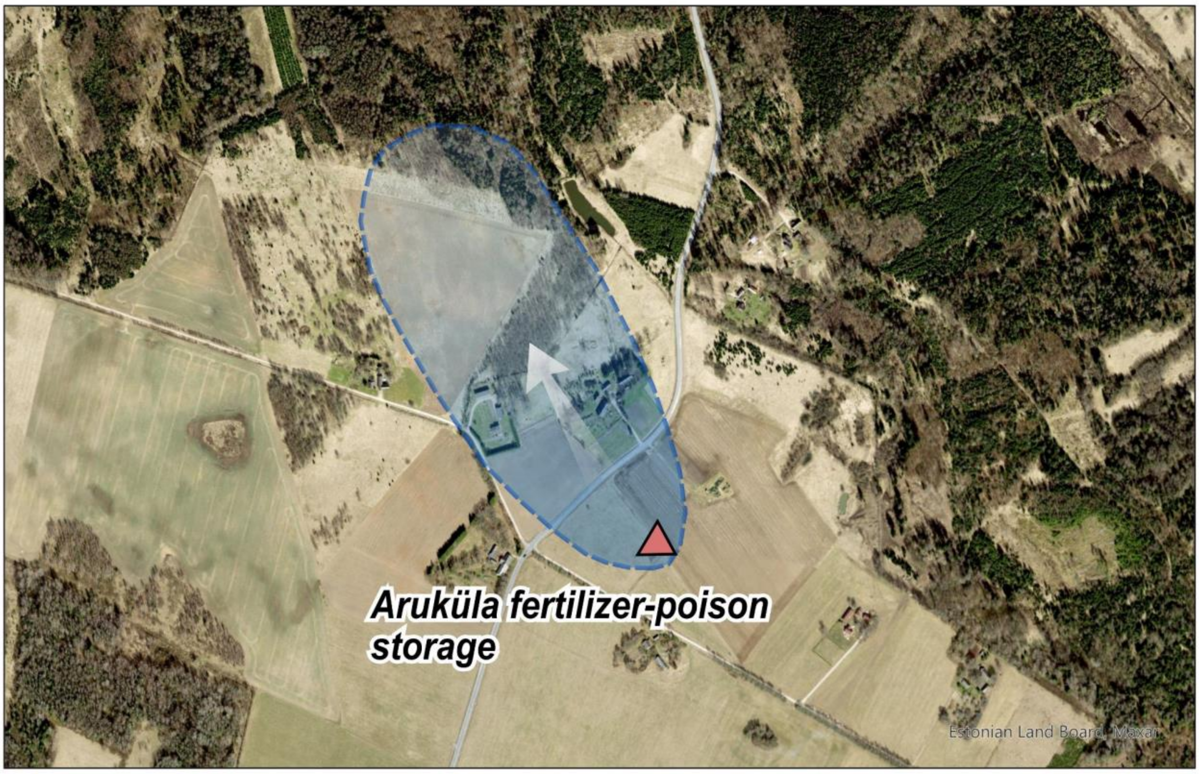
6."Alūksnes putnu fabrika" LLC (“VISTAKO” LLC), poultry farm



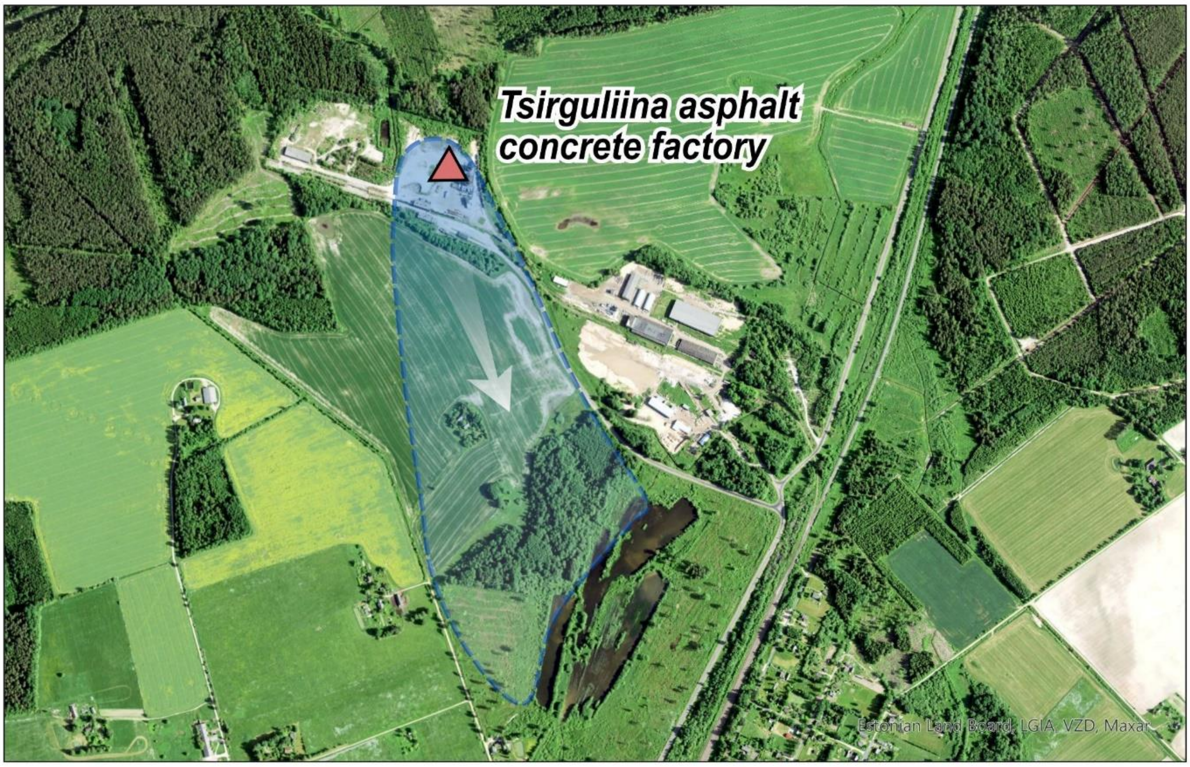
7. "KUNTURI" LLC, pig farm

8. "EAST-WEST TRANSIT" LLC gas station "RŪJIENA"

9. Äruküla fertilizer-poison storage

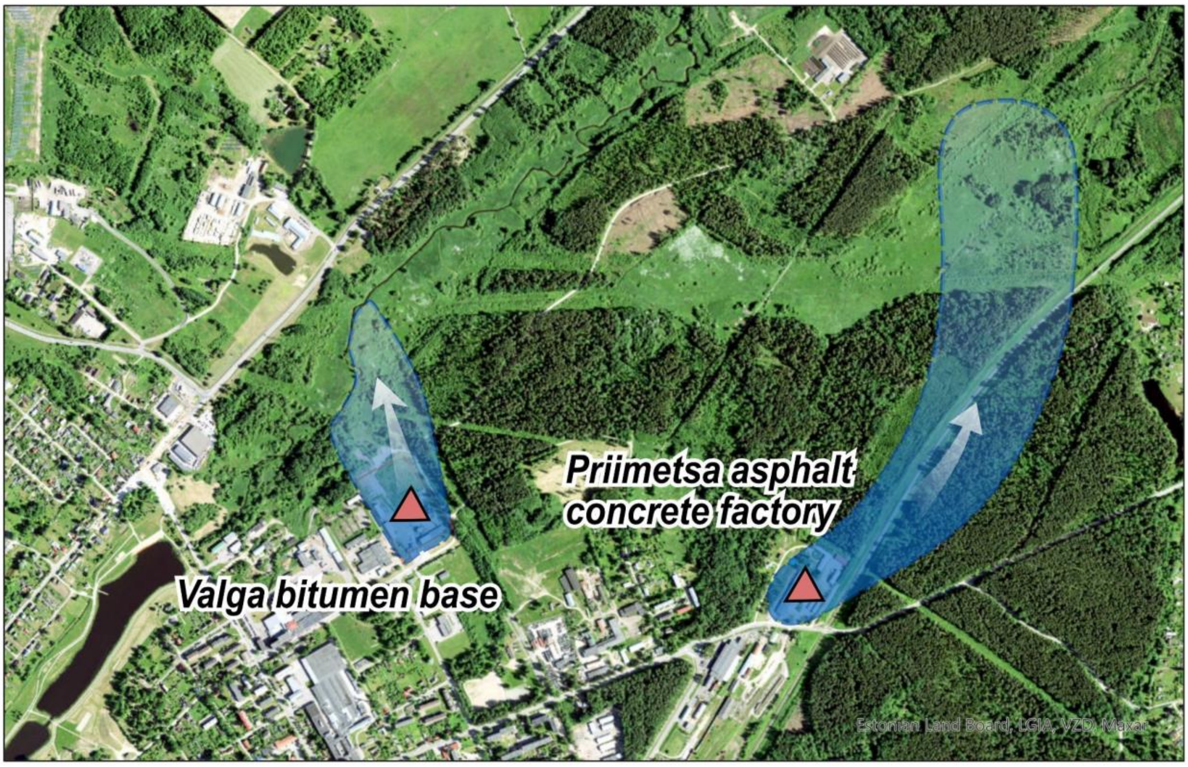


11. Tsirguliina asphalt concrete factory



12.,13. Vilaski rocket base town and car base & Vilaski rocket installation area and nuclear warhead warehouse

14., 15. Valga bitumen base & Priimetsa asphalt concrete factory



16. Tsooru collective farm oil storage

17. Rõuge toxic chemical warehouse