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LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following published papers, which are referred to in the text by Roman numerals.

- **I** **Männik, M.**, Karro, E., Marandi, A., Polikarpus, M., Ani, T., Rosentau, A. (2023). Modified DRASTIC method for groundwater vulnerability assessment in areas with diverse Quaternary deposits. *Hydrology Research, 54*(7), 840–854. https://doi.org/10.2166/nh.2023.009
- **II** **Männik, M.**, Karro, E. (2023). Application of Modified DRASTIC Method for the Assessment and Validation of Confined Aquifer Vulnerability in Areas with Diverse Quaternary Deposits. *Water 15*(20), 3585. https://doi.org/10.3390/w15203585
- **III** **Männik, M.**, Bikše, J., Karro, E., Marandi, A. (2025). A framework for assessing groundwater vulnerability and pollution risk in transboundary aquifers: Insights from the Estonian-Latvian transboundary area. *Journal of Hydrology: Regional Studies 60*. https://doi.org/10.1016/j.ejrh.2025.102525

A table showing the author's contribution to the scientific papers (' minor contribution; * moderate contribution; ** large contribution; *** leading role).

	I	**II**	**III**
Original idea	*	***	***
Study design	***	***	***
Data collection	***	***	***
Analysis and interpretation	***	***	***
Manuscript writing	***	***	***

1. INTRODUCTION

Groundwater is an essential resource that supports ecosystems, agriculture, and drinking water supplies across the world. It is crucial for sustaining life, economic development, and preserving the health of our natural environment, yet its quality is increasingly threatened by urbanisation, industrial activities, and intensive agriculture. Identifying areas where groundwater is most vulnerable to contamination is therefore critical for sustainable management, land-use planning, and policymaking (Gogu & Dassargues, 2000). The degree of natural groundwater protection depends on the pathway of the contaminants from the land surface to the aquifer (Zwahlen, 2004), which is controlled by the properties of the soil, the vadose zone, and the aquifer itself (Vrba & Zaporozec, 1994).

Groundwater vulnerability assessment provides a framework for classifying areas according to their sensitivity to pollution. A key concept here is intrinsic vulnerability, which describes the natural ability of geological and hydrogeological settings to protect the aquifer. Among the various approaches developed for this purpose, index-based methods are most widely applied (Vrba & Zaporozec, 1994). These combine parameters that describe aquifer protection into a single numerical index. Each parameter is assigned a rating, often weighed to reflect its relative importance, and the results are summed to produce a score that indicates the relative vulnerability of different areas to contamination (Vrba & Zaporozec, 1994).

Among index-based methods, the DRASTIC method (Aller et al., 1987) is one of the most widely used (Babiker et al., 2005; Banda et al., 2024; Dindi et al., 2024; Gómez-Mena et al., 2024; Jamaa et al., 2024; Kong et al., 2019; Ouzerbane et al., 2022; Slessarev et al., 2024) due to its clarity, adaptability and ability to integrate diverse hydrogeological data. The DRASTIC method evaluates vulnerability through seven parameters: depth to water, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity. Many studies have modified the method to better reflect local hydrogeological conditions (Liu et al., 2022; Rauf et al., 2022; Zhang et al., 2022). In addition, land use has been added as an eighth parameter, creating the DRASTIC-L method, which assesses actual pollution risk by linking natural vulnerability with anthropogenic pressures (Abduljaleel et al., 2024; Javadi et al., 2022).

Existing studies mainly focus on assessing groundwater vulnerability in unconfined aquifers (Abduljaleel et al., 2024; Ahmed et al., 2022; Fusco et al., 2024; Liu et al., 2022; Moustafa, 2019). In these settings, the DRASTIC framework performs well, as vulnerability is mainly determined by the depth of the water table and the properties of the unsaturated zone. In contrast, confined aquifers are influenced additionally by protective factors, such as a layer of clayey sediments and hydraulic pressure from the piezometric head.

Such conditions are common in formerly glaciated areas, where heterogeneous Quaternary deposits form a complex upper layer above the first bedrock aquifer. This two-layer system, with a variable Quaternary cover on top and the first bedrock aquifer below, is characteristic of Estonia and much of the Baltic region. The Quaternary deposits often act as a confining layer, as it is frequently clayey and tens of meters or sometimes hundreds of meters thick (Raukas, 2009). In places, the piezometric head of the aquifer is above the land surface, creating artesian conditions and spring outflows. These areas are naturally well protected, as hydraulic pressure prevents downward contaminant transport.

This two-layer hydrogeological system is also relevant from a water management perspective. The shallow Quaternary aquifers, while more vulnerable, play an essential role by sustaining local ecosystems and recharging the deeper confined aquifers (Hunt et al., 2023). However, the first bedrock aquifer is the main source of drinking water, widely used for centralised water supply (Solovey et al., 2021). Because of high dependence on this resource, its vulnerability assessment is critical for ensuring the quality of drinking water and supporting sustainable management.

Conventional methods, such as the original DRASTIC method, fail to capture the dynamics between the two layers. Because the D-parameter only considers the depth to the piezometric surface, areas with shallow groundwater or artesian conditions may be misclassified as highly vulnerable, even though they are well protected. At the same time, the variability of the Quaternary sediments, ranging from protective clays to highly permeable sands, creates strong local contrasts in aquifer protection and contributes to quality issues (Koit et al., 2023).

These complexities highlight the need for more precise vulnerability assessment methods that can account for confined aquifers and the properties of the overlying sediments. To address this gap, a modified version of the DRASTIC method was developed in this dissertation. The approach incorporates modifications to three parameters related to the confining layer of Quaternary sediments in order to assess the vulnerability of the first bedrock aquifer more precisely.

The main goal of this dissertation is to develop and evaluate an improved methodology for assessing the vulnerability of confined aquifers, focusing on the first bedrock aquifer in Estonia. The specific objectives are as follows:

- Improve the performance of the DRASTIC method to better describe the conditions of confined aquifers and the protective role of Quaternary sediments.
- Apply the modified method in representative study areas in Estonia and in the Estonian-Latvian transboundary region, characterising contrasting geological settings (carbonate versus sandstone aquifers, thin versus thick Quaternary cover).
- Evaluate the performance of the modified method by comparing it with the existing Estonian vulnerability maps, and by correlating with groundwater nitrate concentrations, and sensitivity analyses for parameter influence.
- Extend the approach by incorporating land use (DRASTIC-L) in order to assess pollution risk that combines both the natural vulnerability and anthropogenic pressures.
- Demonstrate the applicability of the modified method in formerly glaciated areas and highlight its significance for groundwater protection and sustainable management in both national and transboundary contexts.

2. GEOLOGICAL AND HYDROGEOLOGICAL SETTING

Estonia is situated in the northwestern part of the East European Platform. The crystalline basement is overlain by sedimentary rocks of the Ediacaran, Cambrian, Ordovician, Silurian, and Devonian ages, which in turn are overlain by Quaternary deposits formed during the last glaciation period. Continental ice retreated from Estonia between 15 and 13 ka BP (Kalm, 2006), leaving behind a wide range of landforms and sediments, including glaciofluvial sands and gravels, glaciolacustrine clays and sands, glacial moraine sediments, and alluvial sediments (Raukas, 2009). The thickness of the Quaternary cover varies from a few meters in northern and central Estonia to more than 100 m and up to 200 m in the southern upland areas and in buried valleys. The climate is moderately cool and humid in Estonia, with the average annual precipitation around 500–750 mm. Net recharge varies from 10 to 300 mm/year (Vallner & Porman, 2016).

In northern and central Estonia, the first bedrock aquifer is the Silurian-Ordovician aquifer system, composed of limestones and dolomites. The uppermost 30 m is highly cavernous, allowing intensive water exchange. The hydraulic conductivity of the Silurian-Ordovician aquifer system is 10–50 m/d (Perens & Vallner, 1997). In places where the Quaternary cover is thin, groundwater in these highly cavernous limestones is highly vulnerable to surface pollution (Perens & Vallner, 1997).

In southern Estonia, the first bedrock aquifer is mainly the Middle-Devonian aquifer system, composed of sandstones. Compared to carbonates, these rocks typically have lower hydraulic conductivity (from 2 to 15 m/d; Solovey et al., 2021), and therefore, the vulnerability to contamination is lower. In some areas, the Upper-Devonian aquifer system, consisting of dolomites, forms the first bedrock aquifer. With hydraulic conductivity values ranging from 1 to 50 m/d (Solovey et al., 2021), these carbonate aquifers tend to be more vulnerable than the Middle-Devonian terrigenous aquifer system.

The heterogeneity of the Quaternary cover has direct hydrogeological implications, as it controls the degree of protection provided to the first bedrock aquifer. Aquifer conditions vary from unconfined to confined depending on the thickness and type of the overlying sediments. The clayey or till deposits act as effective confining layers, while sandy sediments and thin covers leave aquifers exposed to pollution. This variability makes Estonia a great setting to test and refine groundwater vulnerability assessment methods.

To apply and further develop the modified DRASTIC methodology, four study areas were selected in Estonia (Figure 1) and in the Estonian-Latvian border region (Figure 2). These represent a range of geological settings where the characteristics of the Quaternary cover and the type of the first bedrock aquifer differ significantly. The study areas provide examples of thin versus thick Quaternary deposits, carbonate versus sandstone aquifers and national versus transboundary contexts.

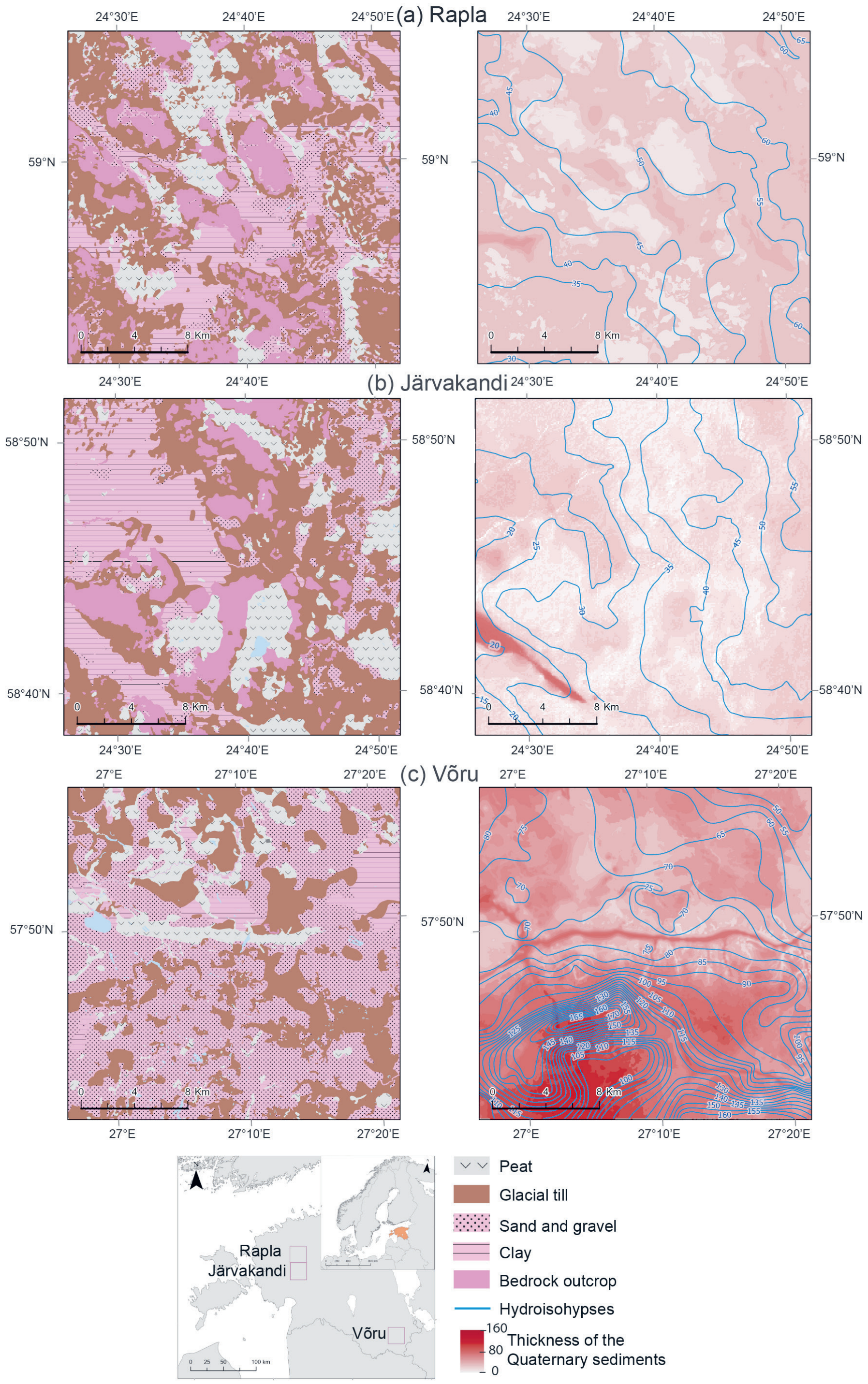

Figure 1. Location of the Rapla (a), Järvakandi (b), and Võru (c) study areas in Estonia. Quaternary deposits and hydroisohypses of the first bedrock aquifer in the study areas (Geological Survey of Estonia, 2025) (based on Paper I – Männik et al., 2023, and Paper II – Männik & Karro, 2023).

The Järvakandi study area (625 km^2) is part of the Estonian geological base map (Geological Survey of Estonia, 2025) and is located in central Estonia. The first bedrock aquifer in the study area is the Silurian-Ordovician aquifer system, composed of limestones and dolomites. The Quaternary cover is relatively thin, generally less than 5 m, and consists mainly of glacial till, glaciolacustrine clays, and glaciofluvial sands and gravels. This variability makes Järvakandi a suitable test site for evaluating how the modified method works in different sediment types and confined vs unconfined conditions.

Similarly, the Rapla study area (625 km^2) is also located in central Estonia and has the same Silurian-Ordovician aquifer system as Järvakandi. Its Quaternary cover is very thin (<5m), and in some places absent, leaving the carbonate aquifer highly vulnerable to pollution. Some areas of thicker clay-rich cover make the aquifer confined. Quaternary thickness reaches up to 70 m in buried valleys (Geological Survey of Estonia, 2025), creating contrasts in the vulnerability degree in the area.

In contrast to Järvakandi and Rapla, the Võru study area (625 km^2) is located in southeastern Estonia, and the first bedrock aquifer here is the Middle-Devonian aquifer system composed of sandstones. The Quaternary cover is thick and heterogeneous, reaching 100–190 m in the Haanja upland and 60–80 m in the Võru valley (Geological Survey of Estonia, 2025). The cover mostly consists of moraines and glaciofluvial deposits, often forming confined aquifer conditions and providing strong natural protection.

The Estonian-Latvian study area (4000 km^2) was delineated to ensure comprehensive coverage of groundwater management issues in the region, and for that, the existing groundwater bodies, transboundary surface water bodies and the Baltic Sea coastline were considered (Solovey et al., 2021). Most of the land is covered by forest and semi-natural areas, accounting for 63% of the total area. Agricultural land occupies another significant portion, 32%. The Quaternary cover varies from 5 to 10 m in Estonia to more than 80 m in the uplands of Alūksne (Latvia) and Haanja (Estonia). The main aquifer systems are the Quaternary aquifers, the Upper-Devonian carbonate aquifer (dolomites and limestones) and the Middle-Devonian (Estonia)/Upper-Middle-Devonian (Latvia) aquifer systems. The carbonate aquifers are more vulnerable due to higher hydraulic conductivity, whereas the sandstones are better protected. This region provides an important test case for applying the modified method in a transboundary context, where geological variability is combined with differences in data and management approaches.

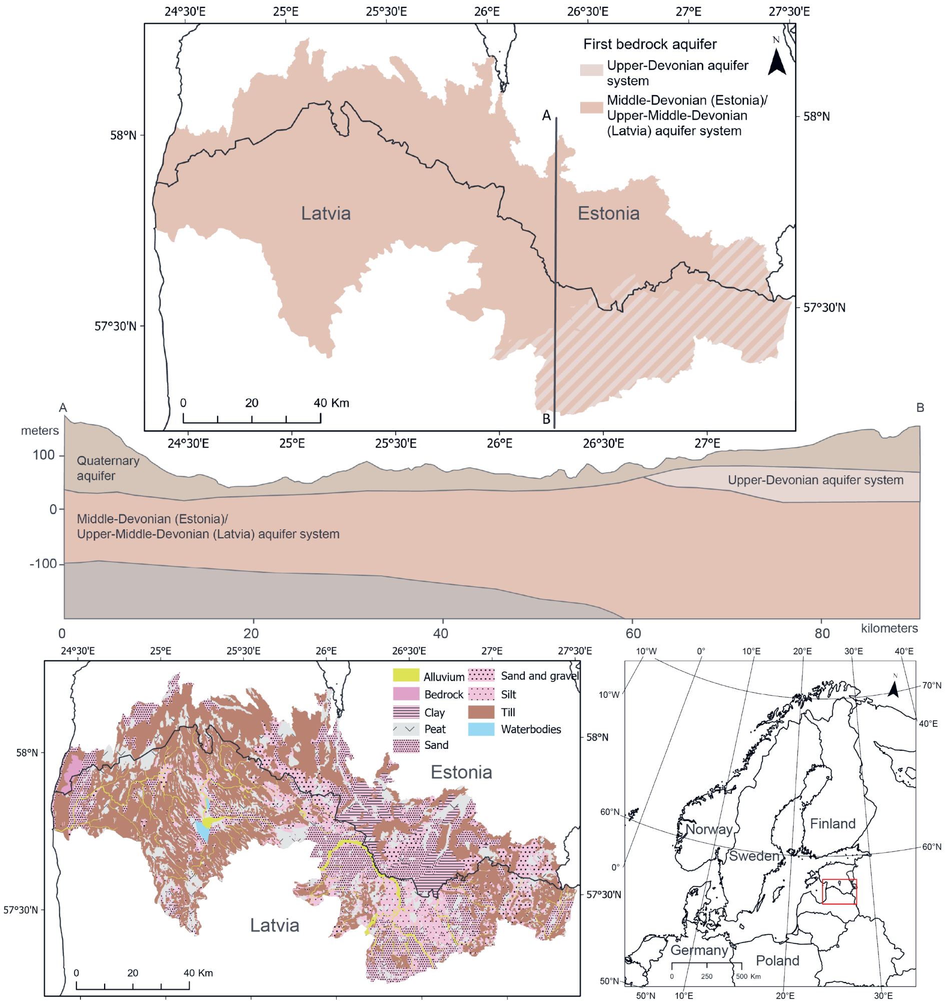

Figure 2. The location of the Estonian-Latvian transboundary area and the first bedrock aquifer and Quaternary sediments maps. Cross-section of the unconfined Quaternary aquifer and confined first bedrock aquifer (based on Paper III – Männik et al., 2025).

3. MATERIAL AND METHODS

3.1. DRASTIC method

The assessment of the intrinsic groundwater vulnerability is conducted using the index-based DRASTIC method. The DRASTIC method was developed by the U.S. Environmental Protection Agency for evaluating the vulnerability of groundwater to contamination (Aller et al., 1987). The acronym DRASTIC refers to seven parameters: the depth to the water table (D), net recharge (R), aquifer media (A), soil media (S), topography (T), the impact of the vadose zone (I), and hydraulic conductivity (C). The parameters are scored on a scale from 1 to 10 based on the level of vulnerability, where 1 means the lowest vulnerability and 10 the highest. Additionally, parameters receive a weight between 1 and 5 to highlight their relative importance in the overall assessment.

The vulnerability index, which represents the potential risk of groundwater contamination, is a weighted sum of the parameters:

$$D_i = \sum_{J=1}^{n} \left(W_j \times R_j\right) \tag{1}$$

where Di is the vulnerability index for a mapping unit, W_j is the weight of parameter j, R_j is the rating of parameter j, and n is the number of parameters used in assessment, 7 for DRASTIC and modified DRASTIC, 8 for modified DRASTIC-L. A higher vulnerability index suggests a greater groundwater contamination risk.

The parameters for the vulnerability assessment methods, along with their respective weights, are described in Table 1, while Table 2 provides the parameter ranges and ratings information.

Table 1. The modified DRASTIC and modified DRASTIC-L method parameters and their weights

Parameter	Description	Weight
D – Depth to groundwater table	Depth of the piezometric head compared to the bedrock surface. Pollution risk is lower when the piezometric head is above the bedrock surface and higher in areas where it is below the bedrock surface.	5
R – Net recharge	Represents the amount of water that infiltrates down through the soil and vadose zone to reach the water table. Recharging water facilitates the transport of pollutants to the water. A higher recharge value indicates a more significant potential for groundwater contamination.	4
A – Aquifer media	Refers to the sediments that form the aquifer. Larger grain sizes and more fractures and openings lead to higher permeability, which lowers the aquifer's capacity to attenuate contaminants.	3
S – Quarternary sediment type	Relates to the characteristics of the Quaternary sediments situated above the first bedrock aquifer, which affect the amount of water that can infiltrate into the ground.	5
T – Topography	Represents the slope of the land surface, which determines the likelihood of pollutants either running off or remaining on the surface long enough to infiltrate into the ground.	1
I – Thickness of the Quaternary sediments	Indicates the distance pollutants travel from the ground surface to the bedrock, which directly impacts the vulnerability of the aquifer.	5
C – Hydraulic conductivity	Describes the aquifer's capacity to transmit water and the rate at which contaminants can move within it. Higher hydraulic conductivity is linked to a greater risk of contamination.	3
L – Land use	Refers to the different categories of land use that affect the potential for groundwater contamination. Various land uses, such as urban development, agriculture, or natural vegetation, have distinct impacts on groundwater quality.	5

Table 2. Parameters and ratings used to calculate groundwater vulnerability of the first bedrock aquifer with the modified DRASTIC (Paper I – Männik et al., 2023; Paper II – Männik & Karro, 2023; Paper III – Männik et al., 2025), and pollution risk with the DRASTIC-L method (Paper III – Männik et al., 2025).

D – Depth to groundwater table		**R – Net recharge**		**A – Aquifer media**		**S – Quaternary sediment type**	
Depth of the piezometric head compared to the bedrock surface [a] (m)	Rating	Range (mm/y)	Rating	Type	Rating	Type	Rating
<–10	10	0–50	1	Clay	4	Clay	1
–10…–5	9	50–100	3	Bedrock	4	Bedrock	2
–5…–1	7	100–175	6	Peat	4	Peat	6
–1…0	6	175–250	8	Gravel	6	Gravel	6
0…1	5	>250	9	Sand	6	Sand	7
1…3	3			Till	4	Till	8
3…5	2			Middle-Devonian/Upper-Middle-Devonian aquifer system; sandstone with siltstone interlayers	6		
>5	1			Upper-Devonian aquifer system; dolomite with dolomitic marl	10		
T – Topography		**I – Thickness of the Quaternary sediments**		**C – Hydraulic conductivity**		**L – Land use (modified DRASTIC-L)**	
Slope (%)	Rating	Range (m)	Rating	Range (m/d)	Rating	Type	Rating
0–2	10	0–2	10	0.04–4	1	Artificial surfaces	10
2–6	9	2–5	9	4–12	2	Agricultural areas	8
6–12	5	5–10	7	12–28	4	Forest and semi natural areas	2
12–18	3	10–20	5	28–40	6	Wetlands	1
>18	1	20–40	3	40–80	8	Water bodies	1
		>40	1	>80	10		

[a] piezometric head below the bedrock surface is indicated by a negative value

3.2. Modifications to the DRASTIC method

3.2.1. Conceptual basis for modifying D, S, I parameters

The DRASTIC method was originally designed for assessing the vulnerability of unconfined aquifers, but its application to confined aquifers has been limited, overlooking their hydrogeological complexities. In formerly glaciated regions, like Estonia and Latvia, the bedrock aquifers are often overlain by thick and heterogeneous Quaternary deposits that act as confining layers, altering the infiltration dynamics and the groundwater flow conditions. In this case, contaminant transport is not solely affected by the vadose zone properties but also by the composition and thickness of the overlying Quaternary layer. To address this, three key parameters in the DRASTIC model were conceptually modified: depth to water (D), soil media (S), and impact of the vadose zone (I), as they are the most directly affected by the presence and characteristics of confining Quaternary sediments.

In the original DRASTIC method, the D-parameter represents the vertical distance from the land surface to the water table (Aller et al., 1987). In unconfined aquifers, this value is directly linked to vulnerability: shallow water tables generally correlate with higher vulnerability, and deeper water tables indicate lower contamination risk. However, in confined aquifers, the depth of the piezometric surface may be shallow even if the aquifer is overlain by thick, low-permeability layers. As a result, the classic D-parameter can significantly overestimate vulnerability in confined conditions.

To resolve this, the D-parameter was redefined, and confinement status was assessed by calculating the difference between the piezometric level and the surface of the bedrock (the base of the Quaternary sediments). If the piezometric level lies above the bedrock surface, the aquifer is considered to be confined, and if it lies below, it is unconfined. This approach considers the protective effect of the Quaternary sediments and allows the vulnerability assessment to reflect aquifer pressure and describe areas where the pollution movement is hindered.

In the original DRASTIC method, the S-parameter refers to the soil media, defined as the uppermost layer of unconsolidated material that supports plant growth and influences surface infiltration (Aller et al., 1987). However, in the study areas, the thin soil layer is often not the main barrier to infiltration, and instead, the Quaternary sediments play a more significant role. These sediments often correlate with soil types but offer a more meaningful representation of the hydrogeological conditions controlling contaminant transport. Because of this, the S-parameter was replaced by a Quaternary sediment type parameter to represent the lithological characteristics of the Quaternary deposits, whether that is, e.g. glacial till, sand, clay, or peat. In addition, the parameter weight was increased from 2 to 5, emphasising its greater importance in regions where the protective effect is controlled primarily by the type and properties of the Quarternary deposits.

The I-parameter in the original DRASTIC method describes the impact of the vadose zone, which is the unsaturated layer between the ground surface and the water table that influences how easily contaminants can move toward the aquifer. As the type of vadose zone sediment is already described in the modified S-parameter, the original I-parameter was replaced by the thickness of the Quaternary sediment layer. This allows the method to account for the length of the flow path a pollutant must travel to reach the aquifer. The thicker the protective layer, the lower the vulnerability, as there is greater potential for contaminant attenuation and delay.

3.3. Modified DRASTIC variants: DRASTIC, and DRASTIC-L

In this study, two modified versions of the DRASTIC method were used: modified DRASTIC and modified DRASTIC-L. Both methods are based on the conceptual changes described in the previous section, where the D-, S-, and I-parameters were adapted to better reflect the influence of the confining Quaternary sediments. The modified DRASTIC method focuses on assessing the natural vulnerability of the aquifer, while the modified DRASTIC-L method additionally incorporates anthropogenic impact to estimate actual pollution risk.

The vulnerability index (Di) using the modified DRASTIC method is calculated using Eq. (1) with the following parameters: depth to groundwater (D), net recharge (R), aquifer media (A), Quaternary sediment type (S), topography (T), thickness of the Quaternary sediments (I) and hydraulic conductivity (C).

To take into account human pressures, the modified DRASTIC-L method adds an eighth parameter, land use (L), which assesses diffuse pollution risks from surrounding activities. Recognising its importance, this parameter was given a weight of 5. The resulting vulnerability index (Di), therefore, integrates both hydrogeological and anthropogenic factors, enabling the creation of pollution risk maps. Such maps have been widely emphasised in recent studies (Abduljaleel et al., 2024; Javadi et al., 2022; Kumar & Krishna, 2020; Liang et al., 2024; Ozegin et al., 2024; Sresto et al., 2022) as essential tools that help to identify priority areas for groundwater protection.

3.4. Study areas and data sources

3.4.1. Järvakandi, Rapla and Võru study areas

The data used for the groundwater vulnerability analysis for the geological base map study areas Järvakandi, Rapla and Võru (Paper I – Männik et al., 2023 and Paper II – Männik & Karro, 2023) are presented in Table 3. The acquired data are in the Estonian Coordinate System of 1997 (EPSG:3301). The main source was the Estonian Geological Base Map geodatabase (in a scale of 1:50,000) compiled by the Geological Survey of Estonia. All spatial analysis and map layers used for the vulnerability assessment were processed in ArcGIS software (Esri, 2025).

Table 3. Data sources of the DRASTIC parameters in the geological base map study areas

Parameter	Data source	Scale
D	Estonian Geological Base Map geodatabase (Geological Survey of Estonia 2021); Estonian Nature Information System (Estonian Environment Agency, 2023).	1: 50 000
R	Net infiltration map of Estonia (Vallner & Porman, 2016)	1:200 000
A	Estonian Geological Base Map geodatabase (GSE, 2025)	1: 50 000
S	Estonian Geological Base Map geodatabase (GSE, 2025)	1: 50 000
T	Digital elevation models (10 m resolution) from Lidar elevation data (Estonian Land and Spatial Development Board, 2025)	1: 20 000
I	Estonian Geological Base Map geodatabase (GSE, 2025)	1: 50 000
C	Estonian Geological Base Map geodatabase (GSE, 2025); Hydraulic conductivity data published by (Perens & Vallner, 1997) in *Geology and Mineral Resources of Estonia.*	1: 50 000

3.4.2. Estonian-Latvian transboundary area

The various data sources used for groundwater vulnerability assessment of the Estonian-Latvian transboundary area (Paper III – Männik et al., 2025) are presented in Table 4. In this study area, the primary goal was to harmonise data between the two countries, addressing differences in data availability and quality. The Estonian-Latvian hydrogeological model (Hunt et al., 2023) developed with MODFLOW-6 software, was central to understanding groundwater flow and the broader hydrogeological system. Along with this model, harmonised hydrogeological maps from the EU-Waterres project (https://eu-waterres.eu/web-app/) provided essential input for the analysis.

Table 4. Data sources for the DRASTIC parameters in the Estonian-Latvian transboundary area

Parameter	Data source	Data format, scale/pixel size
D	Estonian-Latvian (EE-LV) transboundary area hydrogeological model (Hunt et al., 2023)	Raster data, 250m
R	Estonian-Latvian transboundary area hydrogeological model (Hunt et al., 2023)	Raster data, 450m
A	Hydrogeological units of the main useful aquifer (EU-Waterres MapPortal)	Vector data, 1:200 000
S	Generalised EE-LV Quaternary sediments map (GSE, 2025; LEGMC, 2019)	Vector data, 1:200 000
T	Digital elevation model from Lidar elevation data (Estonian Land and Spatial Development Board, 2025; LGIA, n.d.)	Raster data, 60m
I	Estonian-Latvian transboundary area hydrogeological model (Hunt et al., 2023)	Raster data, 65m
C	Estonian-Latvian transboundary area hydrogeological model (Hunt et al., 2023)	Raster data, 250m
L	Corine Land cover data (The Copernicus Programme, 2018)	Raster data, 400m

3.5. Vulnerability categories

Once the vulnerability and pollution risk indices (Di) have been calculated, the results are classified into distinct vulnerability or pollution risk categories. Classification is crucial for translating the complex index outputs into usable information, particularly for non-specialist stakeholders involved in water management and land-use planning, where decision-making relies on clearly defined vulnerability classes and map outputs rather than raw index values.

There is no universally accepted classification system for the DRASTIC index, and thresholds can vary between studies depending on the regional context. In this study, the vulnerability index values were divided into five quantile classes, as suggested by Hamza et al. (2015), who divided the percentage range of the vulnerability indices into five classes based on existing studies: “very low” (from 10.00% to 28.99%), “low” from (29.00% to 46.99%), “medium” (from 47.00% to 64.99%), “high” (from 65.00% to 82.99%), and “very high” (from 83.00% to 100%). These ranges were used for mapping the groundwater vulnerability in the Estonian-Latvian transboundary area, and the Di ranges are presented in Table 5.

Table 5. Vulnerability index (Di) values divided into five classes for the Estonian-Latvian transboundary area (Paper III – Männik et al., 2025)

Vulnerability class	Percentage of the Di range (%)	Di values for the first bedrock aquifer (modified DRASTIC)	Di values for the first bedrock aquifer (modified DRASTIC-L)
Well protected	0–28.99	45–83	54–101
Relatively well protected	29–46-99	84–107	102–130
Moderately protected	47–64.99	108–130	131–159
Weakly protected	65–83.99	131–154	160–188
Unprotected	84–100	155–176	189–216

Taking into account the local regulation for groundwater vulnerability assessment defined in the Estonian Water Act, (2019), the values were modified for use in the Estonian mapping context. Considering the Estonian Water Act, the lowest class means well protected areas with almost no risk of groundwater pollution. Therefore, instead of starting from 10%, the lowest class, “well protected”, was assigned values from 0% to 10% of the vulnerability index values. “Relatively well protected” received values from 10.00% to 28.99%, “moderately protected” from 29.00% to 46.99%, “weakly protected” from 47.00% to 64.99%, and “unprotected” from 65.00% to 100%. The resulting Di value ranges are presented in Table 6.

Table 6. Vulnerability index (Di) values are divided into five classes for the geological base map study areas (Paper I – Männik et al., 2023 and Paper II – Männik & Karro, 2023)

Vulnerability class	Percentage of the Di range (%)	Di values for the Järvakandi study area (Paper I – Männik et al., 2023)	Di values for the Rapla and Võru study area (Paper II – Männik & Karro, 2023)
Well protected	0–10.00	78–91	51–101
Relatively well protected	10.00–28.99	92–117	102–133
Moderately protected	29.00–46.99	118–141	134–164
Weakly protected	47.00–64.99	142–166	165–195
Unprotected	65.00–100	167–213	196–225

3.6. Method validation and sensitivity analysis

3.6.1. Vulnerability assessment validation with nitrate concentration

To validate the results of the modified DRASTIC method, nitrate concentration in groundwater was used as a proxy for pollution presence. Nitrate is a commonly used indicator of groundwater contamination. Elevated nitrate levels are typically associated with contamination resulting from anthropogenic and agricultural activities (Kalvāns et al., 2021), making it a relevant tracer for assessing the real-world accuracy of vulnerability maps. In Estonia, monitoring nitrate concentration is a part of the national groundwater quality assessment. In addition to Estonia, nitrogen pollution is a pressing issue in the other Nordic and Baltic countries, therefore being a subject to extensive research and monitoring (Hansen et al., 2019; Højberg et al., 2017; Kitterød et al., 2022)

The Spearman correlation coefficient was used to assess the extent of correlation between the vulnerability assessment results from the DRASTIC method and the nitrate concentration. The Spearman's rank correlation coefficient stands as a nonparametric statistical metric that quantifies the strength of the relationship between two datasets (Laerd Statistics, 2023) and is calculated using the following equation:

$$\rho = 1 - \frac{\sum_{n-1}^{n} d^2}{n(n^2 - 1)}, \tag{2}$$

where ρ is the Spearman's rank correlation coefficient, d represents the difference between the two ranks of each observation, and n is the number of observations. Nitrate concentration data from 59 wells in Rapla and 193 wells in Võru were used from the Estonian Nature Information System database (Estonian Environment Agency, 2023) for validation with nitrate concentration.

3.6.2. Sensitivity analysis

Sensitivity analysis evaluates the contribution of the input parameters to the outcomes of the vulnerability assessment. In this study, the following approaches are used: the single parameter (Napolitano & Fabbri, 1996) and map removal sensitivity analysis (Lodwick et al., 1990).

In single parameter sensitivity analysis, the impact of each parameter on the overall vulnerability index, assigned by the DRASTIC method, is analysed. The theoretical weight assigned to a parameter is compared with its calculated effective weight. The effective weight (W_p) is determined using the following equation:'

$$W_p = \frac{P_R P_W}{Di} \times 100 \tag{3}$$

where P_r is the rating, and P_W is the weight of the parameter P. Di is the vulnerability index.

Map removal sensitivity analysis defines the sensitivity of the vulnerability map when one or more parameters are excluded from the assessment to evaluate the influence of individual parameters on the overall assessment. The sensitivity measure, S, for a given parameter is calculated using the following equation:

$$S = \left(\frac{\left| \frac{\mathrm{V}}{\mathrm{N}} - \frac{\mathrm{V}'}{\mathrm{n}} \right|}{\mathrm{V}} \right) \times 100 \tag{4}$$

where V is the original vulnerability index, calculated using all DRASTIC parameters, and V' represents the perturbed index, computed with fewer parameters. N and n represent the number of parameters used to calculate V and V', respectively.

4. RESULTS AND DISCUSSION

4.1. Performance of the modified DRASTIC method in areas of variable Quaternary cover

Groundwater vulnerability assessment is challenging in areas with a highly variable Quaternary cover above the first bedrock aquifer. These heterogeneous Quaternary sediments strongly influence water quality (Koit et al., 2023), and therefore, a more accurate approach is needed to find areas most at risk of contamination. The existing vulnerability mapping approach in Estonia relies on a manual method developed in the pre-digital era, which is time-consuming and limited in its capacity to capture hydrogeological complexities. To address this, a modified version of the DRASTIC method was used, where the depth to water (D), soil properties (S), and impact of the vadose zone (I) parameters were modified to improve the accuracy of the vulnerability assessment.

The Järvakandi case study area served as the initial test area for the modified DRASTIC method (Paper I – Männik et al., 2023). In this region, the Silurian-Ordovician aquifer is covered by thin but variable Quaternary sediments, mainly composed of till, peat, and clay. To evaluate the impact of the changes to the methodology, three groundwater vulnerability maps were produced (Figure 3): using the original DRASTIC method (Aller et al., 1987), using the modified DRASTIC method, and using the former methodology of groundwater vulnerability assessment in Estonia for assessing the vulnerability of the first bedrock aquifer.

The comparison of the three maps illustrates how differently the methods illustrate aquifer protection, and it reveals the shortcomings of the original DRASTIC method. The original DRASTIC method (Figure 3a) overestimated the vulnerability in areas with artesian conditions or thick protective sediments. Artesian zones and areas with thick clay cover were mistakenly classified as highly vulnerable because the depth to water parameter (D) only considers the depth to the piezometric surface and does not account for aquifer confinement. As a result, the map failed to delineate any well protected areas, even though in many areas, the pressure from the artesian zone hinders the movement of pollutants to the groundwater.

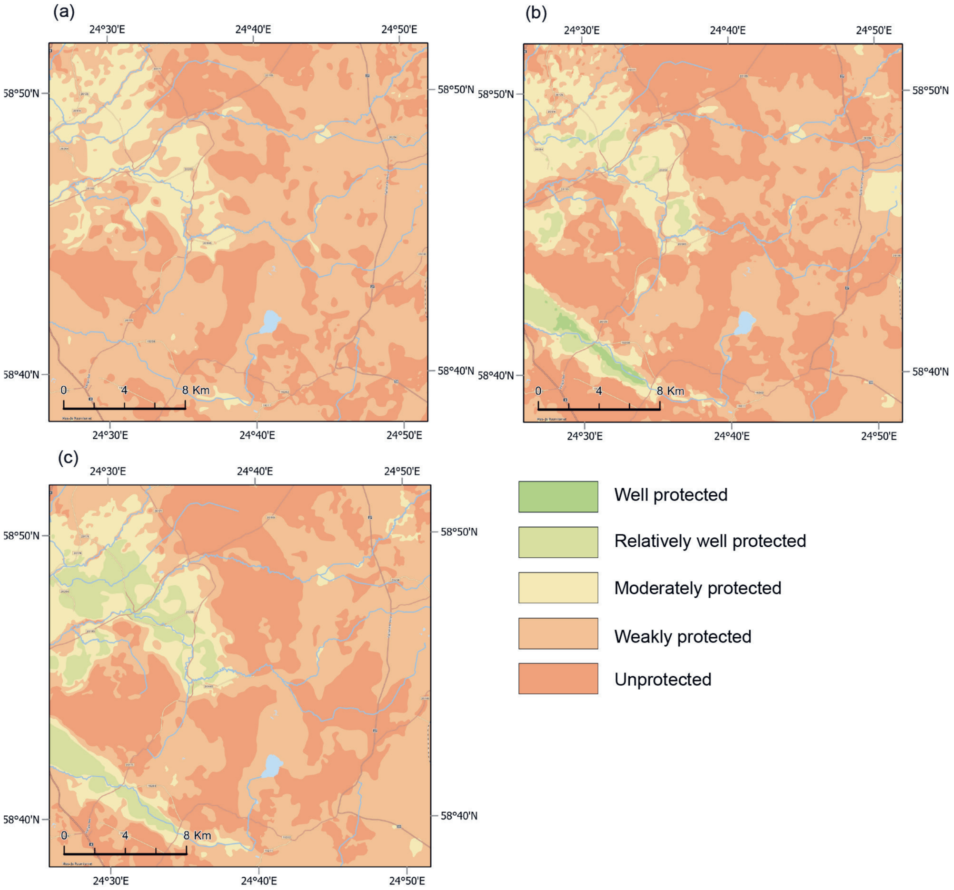

Figure 3. Groundwater vulnerability maps of the Järvakandi study area (based on Paper I – Männik et al., 2023). (a) Map produced using the original DRASTIC method parameters. (b) Map produced using the modified DRASTIC method parameters. (c) Map done using the former Estonian groundwater vulnerability assessment method. River and road data from the Estonian Land and Spatial Development Board (2025).

To improve this, the D parameter was modified to reflect the piezometric level compared to the bedrock surface. As shown in Figure 4a, the original parameter recognised artesian zones and areas with high piezometric levels as unprotected. In contrast, the modified D-parameter values (Figure 4b), recognise the areas of artesian flow as protected areas and the areas with water level lower than the bedrock surface as more unprotected.

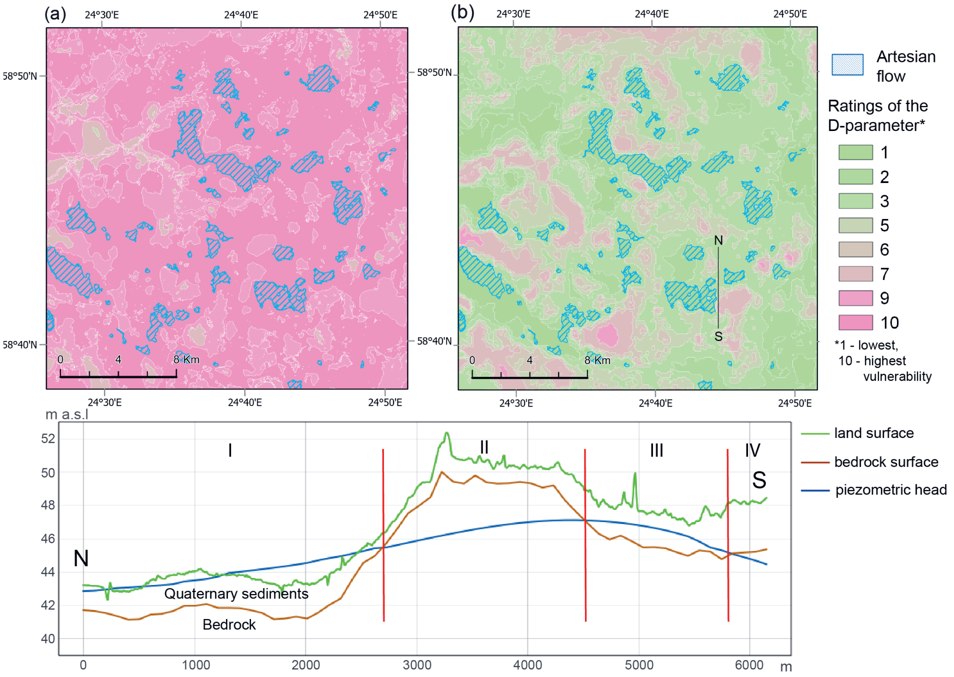

Figure 4. The modification of the D-parameter (based on Paper I – Männik et al., 2023). (a) Ratings of the original D-parameter. (b) Ratings of the modified D-parameter, which compares the piezometric surface with the bedrock surface. The profile N-S shows areas where the vulnerability of the D-parameter is low: areas where the piezometric head is above the land surface (areas of artesian flow; region I) and areas where the piezometric head is above the bedrock surface (regions I and III). In regions II and IV, the vulnerability of the D-parameter is higher due to the piezometric head being below the bedrock surface.

As a result, the modified DRASTIC method (Figure 3b) produced a more realistic vulnerability assessment and distinguished well protected and relatively well protected areas in the study area that the original method failed to identify. The new parameters, at the same time, enabled the delineation of more unprotected zones while also recognising the areas where artesian pressure and thick sediment cover provide substantial protection (Paper I – Männik et al., 2023). The resulting map aligns more closely with local hydrogeological understanding and the former Estonian national vulnerability assessment method (Figure 3c).

In addition to redefining the D-parameter, replacing the soil (S) and vadose zone (I) parameters with Quaternary sediment type and thickness gave stronger weight to the protective effect of clayey sediments and thick till layers, and at the same time highlighted the elevated vulnerability of sandy and thin sediments. For example, in the southwestern part of the study area, where Quaternary deposits reach up to 60 m, the modified method classified these zones as relatively well protected. In contrast, the original DRASTIC had marked the same areas as only weakly protected. Similarly, in the northwest and central part of the study area, up to 5 m thick clay sediments contribute to making the area more protected, as illustrated again only on the modified method map.

The new I-parameter, representing Quaternary thickness, directly accounts for pollutant travel path from the surface to the aquifer. The new S-parameter, which has a higher weight (5) than in the original method, emphasises the role of sediment type in determining natural protection. These adjustments are particularly important in formerly glaciated areas, where heterogeneous Quaternary sediments create contrasts in aquifer vulnerability over short distances. In these areas, the modified method captures the geological reality more accurately than either the original DRASTIC or the former Estonian approach (Paper I – Männik et al., 2023).

4.2. Groundwater vulnerability patterns across study areas

Applying the modified DRASTIC method across different geological settings revealed consistent patterns in how Quaternary cover controls the vulnerability of the first bedrock aquifer. The modified DRASTIC was used to assess the vulnerability and test the effectiveness of the method in the first bedrock aquifer in two additional regions in Estonia: Rapla and Võru (Paper II – Männik & Karro, 2023).

In Rapla, where the Quaternary cover is generally thin, the modified method produced a more balanced distribution of vulnerability classes and reflected better the geological variation when compared to the original DRASTIC method (Figure 5). Small areas of clayey sediments or artesian conditions were recognised as relatively well protected, while peatlands and thicker moraine areas were mostly mapped as moderately protected. The modified map also delineated a larger share of unprotected areas than the original method. A large share of the area remained weakly protected or unprotected, particularly where the Quarternary sediments are very thin.

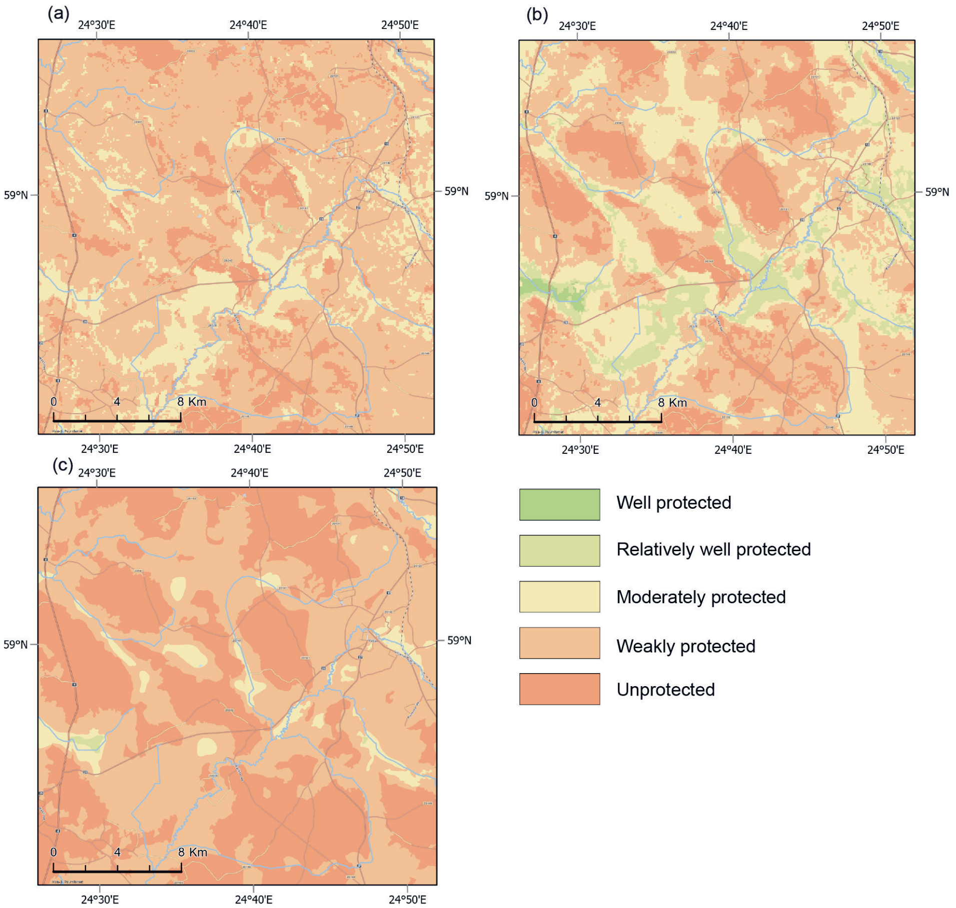

Figure 5. Groundwater vulnerability maps of the Rapla study area (based on Paper II – Männik & Karro, 2023). (a) Map produced using the original DRASTIC method parameters. (b) Map produced using the modified DRASTIC method parameters. (c) Map done using the former Estonian groundwater vulnerability assessment method. River and road data from the Estonian Land and Spatial Development Board (2025).

As a contrast, the Võru study area is covered by thick glacial deposits, sometimes exceeding 100 m in thickness, and the modified DRASTIC reflected this protection provided by the deposits (Figure 6). Most of the region was classified as either well protected or relatively well protected, with some smaller areas of higher vulnerability where the sediment cover is thinner or composed of sandy deposits. Therefore, it can be clearly seen that the characteristics of the Quaternary cover clearly dictate different levels of protection. The results, therefore, emphasise the dominant role of the overlying sediments in determining aquifer vulnerability.

In addition to differences in Quaternary thickness and type, the properties of the aquifer sediments themselves play a role in determining the vulnerability. In Rapla area, the first bedrock aquifer is composed of fractured limestones, which are more susceptible to contaminant transport due to higher hydraulic conductivity. In contrast, the Võru area consists mainly of sandstones that have lower hydraulic conductivity and therefore lower risk of pollution. This difference in bedrock geology lithologies also highlights the contrast in the overall protection between those two areas.

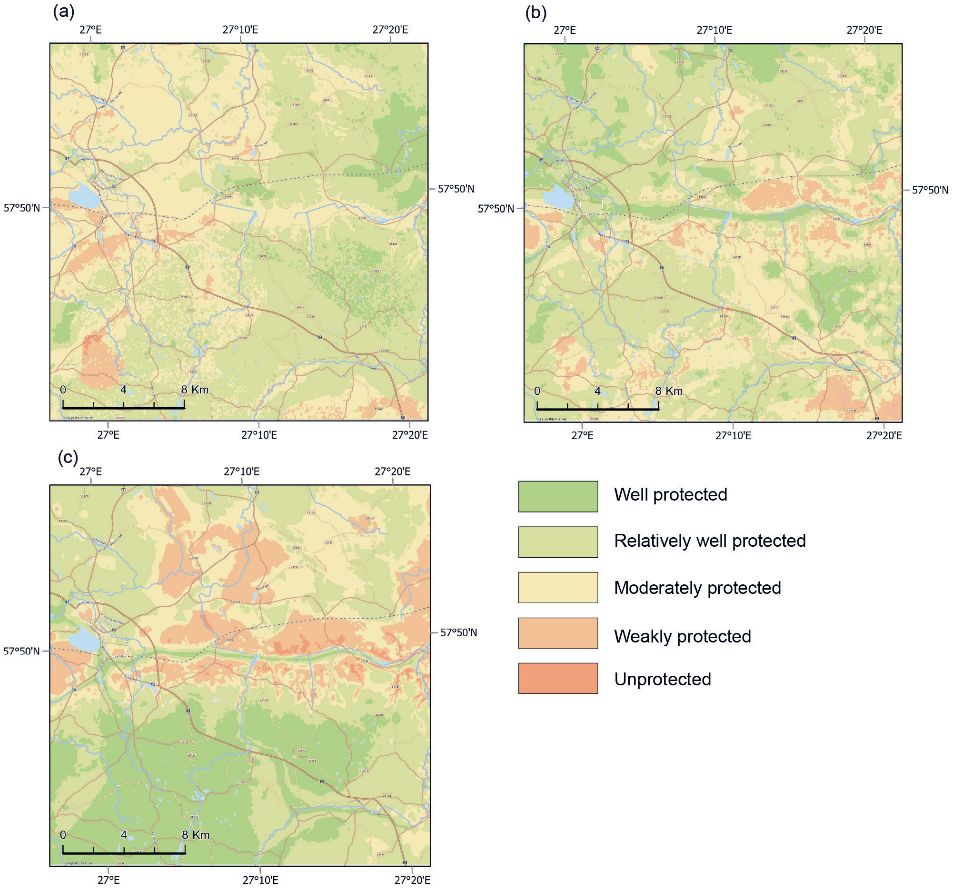

Figure 6. Groundwater vulnerability maps of the Võru study area (based on Paper II – Männik & Karro, 2023). (a) Map produced using the original DRASTIC method parameters. (b) Map produced using the modified DRASTIC method parameters. (c) Map done using the former Estonian groundwater vulnerability assessment method. River and road data from the Estonian Land and Spatial Development Board (2025).

4.3. Sensitivity of the groundwater vulnerability assessment methods

Sensitivity analysis was carried out to evaluate how strongly individual parameters influence the outcome of the vulnerability assessment. Both single-parameter and map-removal analyses were applied in all three study areas to assess the effectiveness of the modified DRASTIC method and to identify which parameters dominate.

The results consistently highlight the importance of parameters related to Quaternary sediments. In Järvakandi, the effective weights showed that the thickness of the Quaternary layer (I) and the sediment type (S) parameter contributed most strongly to the final index, as they exceeded their theoretical weights. In Rapla and Võru, the relative importance of parameters reflected different geological settings. In Rapla, where the Quaternary cover is thin, the thickness of the Quaternary (I) parameter had high weight due to the high sensitivity of thinly covered aquifers to changes in sediment thickness. In Võru, where the Quaternary cover is thick, the sediment type (S) parameter became more influential, reflecting a higher heterogeneity of the deposits. Map-removal analysis further confirmed this result, as the highest variation in the vulnerability indices occurred when the Quaternary thickness or type parameters were removed (Paper I – Männik et al., 2023; Paper II – Männik & Karro, 2023).

The sensitivity analysis of the Estonia-Latvia transboundary area modified DRASTIC map confirmed these general patterns but also revealed the importance of aquifer type and land use. For the first bedrock aquifer, the Quaternary sediment type (S) had the greatest weight, emphasising that confined aquifers rely on their overlying sediments for protection. In the DRASTIC-L assessment, land use showed significant variability and stressed the importance of anthropogenic activity in shaping pollution risk (Paper III – Männik et al., 2025).

In all studied regions, the effective weight of the depth to water (D) parameter was lower than its theoretical weight. This observation suggests the abundance of areas where the piezometric head is making the aquifer confined and protected against pollution by being above the bedrock surface and making the aquifer confined. This emphasises the importance of modifying the vulnerability assessment methods to take into account local hydrogeological complexities.

4.4. Nitrate concentration in groundwater to validate the groundwater vulnerability assessment

Nitrate concentration in groundwater was used as a proxy indicator for contamination to validate the groundwater vulnerability maps. Spearman's correlation was applied to compare nitrate concentration data from monitoring wells with the vulnerability index values obtained from both the original and the modified DRASTIC methods. For this, 59 wells from the Rapla and 193 wells from the Võru study area were used, with depth reflecting hydrogeological conditions: In Rapla, shallow wells (<20 m) were chosen from the uppermost cavernous aquifer zone, whereas in Võru, deeper wells were used, corresponding to the thick Quaternary cover in that area (Paper II – Männik & Karro, 2023).

The results of the correlation analysis indicated a stronger correlation between the nitrate concentration and the modified DRASTIC map compared to the original method. In Rapla, the correlation improved from 0.27 to 0.42, while in Võru it increased from near zero to 0.23 (Paper II – Männik & Karro, 2023). Although these values show that the modified method reflects the vulnerability better, the overall correlations remain modest, especially compared to other studies (Goodarzi et al., 2022; Kardan Moghaddam et al., 2022; Kumar & Krishna, 2020).

There are several factors that contribute to these relatively low correlations. Firstly, in both Rapla and Võru, the pollution levels are lower, as only 44% of the area is being used for agriculture (The Copernicus Programme, 2018). Secondly, Estonia typically has a background level of zero nitrates in groundwater, and therefore any detectable concentration is considered an anthropogenic input. This makes nitrate a very sensitive but also highly variable indicator. Third, the extensive monitoring of nitrates in Estonia provides dense coverage, which increases the likelihood of finding wells where nitrate is absent, yet the vulnerability index indicates a high level of vulnerability.

Overall, nitrate correlation supports the conclusion that modified DRASTIC offers a better representation of aquifer vulnerability than the original approach. However, the modest correlation values highlight the limitations of using nitrate as a sole validation measure, particularly in regions with generally low pollution levels. Therefore, a combination of different validation approaches (including, e.g. infiltration time analysis) is required to comprehensively assess the reliability of vulnerability maps.

4.5. Application of the modified DRASTIC method in a transboundary area

The Estonian-Latvian study area provided an opportunity to evaluate the applicability of the modified DRASTIC method in a transboundary context (Paper III – Männik et al., 2025). Because aquifers extend across political boundaries, their sustainable use requires assessment methods that can be applied consistently on both sides of the border. This case, therefore, tested in addition to the effectiveness of the method, also its value for cross-border groundwater management.

The geological patterns across the Estonian-Latvian were consistent with those observed in the Estonian case studies (Figure 7). Lithology of the bedrock aquifer plays a decisive role in groundwater vulnerability. The Upper-Devonian aquifer system, composed mainly of dolomites, was more vulnerable to pollution due to the higher hydraulic conductivity of the carbonate rocks, whereas the Middle-Devonian/Upper-Middle-Devonian sandstone aquifer showed lower vulnerability. In both aquifer types, variations in protection level are further influenced by the thickness and type of the overlying Quaternary deposits. These findings align with the general patterns identified in Rapla and Võru, further strengthening the conclusion that both the Quaternary cover and aquifer lithology determine groundwater vulnerability (Paper III – Männik et al., 2025).

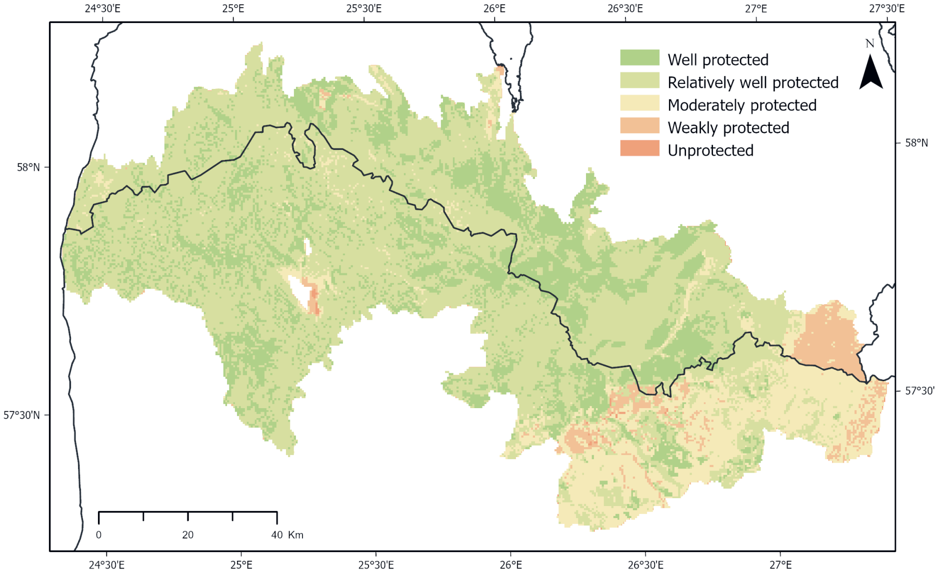

Figure 7. Vulnerability of the confined first bedrock aquifer based on the modified DRASTIC method in the Estonian-Latvian pilot area (based on Paper III – Männik et al., 2025).

A critical challenge that was identified in the Estonian-Latvian study area was the difference in data availability and mapping resolution between the two countries. This discrepancy resulted in abrupt transitions in vulnerability classifications along the border. These inconsistencies emphasise the importance of harmonising cross-border data to ensure reliability and accuracy, as also noted by Flem et al. (2022). Without such efforts, vulnerability maps might reflect differences in input data rather than true hydrogeological variation (Paper III – Männik et al., 2025).

4.6. Groundwater pollution risk assessment

To move from intrinsic vulnerability to actual contamination risk, the DRASTIC-L method was applied to the first bedrock aquifer in the Estonian-Latvian study area (Paper III – Männik et al., 2025). By incorporating land use as an additional parameter, the method captures the combined effect of geological conditions and human activity.

The resulting map (Figure 8) shows that the highest pollution risk occurs where intensive agricultural land use coincides with the presence of highly permeable Quaternary sediments, like sand and gravel. In these areas, natural and anthropogenic conditions align to create conditions of high pollution risk. Conversely, lower risk zones are found in areas with less intensive land use, such as forests and semi-natural areas, and those covered by thick till or clay layers.

Including land use in the assessment highlights an important finding: natural protection does not always correspond to low contamination risk. Even areas classified as relatively well protected in hydrogeological terms might become higher risk zones due to intensive land use. At the same time, naturally vulnerable areas may remain at lower risk if they are dominated by forest or semi-natural area cover. This observation aligns with other studies (Goodarzi et al., 2022; Kumar & Krishna, 2020), which have shown that land use significantly influences pollution risk in aquifers. By combining natural vulnerability and land use, the modified DRASTIC-L method becomes a valuable tool for identifying priority areas where more targeted and effective groundwater protection measures are needed.

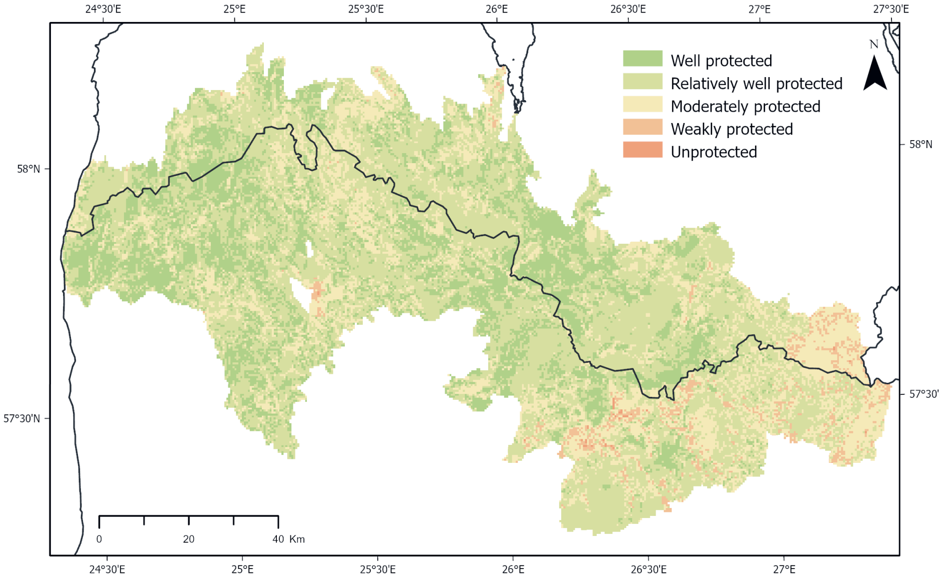

Figure 8. Pollution risk of the confined first bedrock aquifer based on the modified DRASTIC-L method (based on Paper III – Männik et al., 2025).

4.7. Broader implications for groundwater management

The study presents a new approach to groundwater vulnerability assessment designed specifically for confined aquifers in formerly glaciated regions. The hydrogeological conditions addressed here, where a bedrock aquifer is covered by heterogeneous Quaternary sediments, are widespread across Northern Europe and North America. The methodological modifications proposed in this study, therefore, offer a transferable framework that can be applied in such settings, enabling more accurate assessments of confined aquifers and supporting sustainable groundwater management.

Within Estonia, the findings of this study demonstrate that the modified DRASTIC method provides a more reliable and practical tool to assess the vulnerability of the first bedrock aquifer than the currently used approach. The current Estonian vulnerability assessment method, developed in the pre-digital era, is based on manual interpretation of geological maps and has remained unchanged for decades. While it has served as an important baseline, it is time-consuming, lacks transparency, and does not adequately capture hydrogeological complexities. In contrast, the modified DRASTIC is a GIS-based framework that provides results more time-efficiently and is consistent with local hydrogeological understanding. Replacing the existing national approach with the modified DRASTIC would modernise Estonia's groundwater vulnerability assessment, making it more efficient, transparent and in line with up-to-date scientific knowledge.

Beyond intrinsic vulnerability, this dissertation also shows the value of incorporating land-use information into groundwater protection frameworks. By applying the DRASTIC-L method, it is possible to link natural vulnerability with actual pollution pressures, and with this, identify regions where aquifers are at the greatest risk of pollution. This is particularly relevant in agricultural regions, where nitrate pollution is a major concern. Including pollution risk assessment as a management tool would allow authorities to prioritise protection measures in high-risk zones, optimise monitoring networks and inform land planning.

Finally, the results of this study also provide a scientific basis for updating the legislation in Estonia concerning groundwater vulnerability, ensuring that policies are based on the latest methods available. A combined approach of natural vulnerability mapping and pollution risk assessment provides a more comprehensive input for preparing the Water Management Plans to fulfil the EU Water Framework Directive or Nitrate Directive requirements.

5. CONCLUSIONS

The aim of this thesis was to develop and evaluate an improved methodology for assessing the vulnerability of confined aquifers, with a particular focus on the first bedrock aquifer in Estonia. By modifying the DRASTIC method to account for the protective role and variability of the Quaternary sediments, the study provides a framework suited for the hydrogeological conditions of formerly glaciated regions.

The main conclusions of the thesis are as follows:

1) The modified version of the DRASTIC method improves groundwater vulnerability assessment results for confined aquifers by redefining the D-, S-, and I-parameters to reflect the piezometric conditions, Quaternary sediment type, and sediment thickness. The modified version of the method provides results that align better with the hydrogeological reality and assessments done with the national method, while also being more efficient and transparent.

2) Across all study areas, the thickness and type of the Quaternary sediments are the main parameters that determine the level of groundwater protection. Furthermore, aquifer lithology has a strong impact. Thin or sandy deposits and fractured limestones were linked with high vulnerability, whereas thick beds of glacial tills, clays, and sandstones provided stronger protection.

3) Application in the Estonian-Latvian transboundary area demonstrated that the method is applicable in diverse and transboundary settings. However, differences in data resolution between countries highlighted the need for harmonised datasets in order to produce reliable joint assessments.

4) By integrating the land-use parameter for pollution risk mapping (the DRASTIC-L method), the method identifies areas where vulnerable hydrogeological settings overlap with anthropogenic pressure. This helps to reveal high-risk areas and shows that natural vulnerability alone cannot predict real groundwater contamination risk.

5) Correlation of the groundwater vulnerability assessment results with groundwater nitrate concentrations demonstrated that the modified method performs better than the original DRASTIC method. However, the modest correlation values highlight the limitations of using nitrate as a sole validation measure, particularly in regions with generally low pollution levels.

6) The approach has practical and policy relevance both internationally and in Estonia. The method provides a transferable framework for other formerly glaciated regions, where confined aquifers are the key drinking water resource. For Estonia, replacing the outdated manual method with the modified DRASTIC would modernise the groundwater vulnerability assessment.

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SUMMARY IN ESTONIAN

Põhjavee kaitstuse hindamine kvaternaarisetetega kaetud põhjaveekihtides kasutades kohandatud DRASTIC meetodit

Põhjavesi on oluline maapõueressurss, mis toetab ökosüsteeme ja põllumajandust ning on peamiseks joogiveeallikaks pea ligi poolele maailma elanikkonnast. Ometi on põhjavesi tundlik reostumisele, mida mõjutab linnastumine, tööstustegevus ja põllumajanduse intensiivistumine. Põhjavee kvaliteedi säilimises omab olulist rolli maakasutuse planeerimine ja põhjavee jätkusuutlik majandamine, sest hästi läbimõeldud otsused aitavad oluliselt vähendada selle reostumise riski.

Põhjavee kaitstuse hindamine aitab tuvastada piirkonnad, kus reostuse jõudmine põhjaveeni on kõige tõenäolisem ja kiirem. Põhjavee loodusliku kaitstuse taseme ehk reostusohtlikkuse suuruse määrab teekond reostuse allikast põhjaveekihini. Seetõttu kasutatakse põhjavee kaitstuse hindamiseks konkreetse piirkonna geoloogilisi ja hüdrogeoloogilisi tingimusi. Kaitstuse hindamisel on levinumad indeksipõhised meetodid, kus igale kaitstust iseloomustavale omadusele (nt veetaseme sügavus või põhjaveekihi tüüp) määratakse punktide skoor. Kõiki parameetreid kokku liites saadakse üldine suhteline põhjavee kaitstuse skoor, mis võimaldab eri piirkondi omavahel võrrelda.

Kõige tuntum indeksipõhine põhjavee kaitstuse hindamise meetod on DRASTIC-meetod, mida on rakendatud üle maailma erinevates geoloogilistes tingimustes. Meetodi populaarsus tuleneb selle selgest parameetrite põhisest defineerimisest ja heast kohandatavusest. DRASTIC hindab põhjavee kaitstust seitsme parameetri kaudu: veetaseme sügavus, netoinfiltratsioon, põhjaveekihi omadused, mulla omadused, topograafia, aeratsioonivööndi mõju ja filtratsioonimoodul. Klassikaline DRASTIC-metoodika töötab hästi piirkondades, kus põhjaveekihid on surveta ja reostus liigub otse maapinnalt põhjaveeni.

Samas ei kirjelda DRASTIC meetod piisavalt täpselt olukordi, kus põhjaveekihid on survelised ja kaetud mitmekesiste kvaternaarisetetega. Antud tingimused on iseloomulikud endistele jäätumisaladele, sealhulgas Eestile. Kaheosalises süsteemis, kus pealmise kihi moodustavad kvaternaarisetted ja nende all paikneb esimene aluspõhjaline põhjaveekiht, on pinnakattel, nii selle paksusel kui ka tüübil, oluline roll kaitstuse taseme kujundamisel. Aluspõhjalise põhjaveekihi peal lasuvad setted võivad muuta veekihi kohati surveliseks, mis suurendab kaitstust, kuna põhjavee kõrge survetase takistab reostuse liikumist allapoole ja vähendab põhjavee reostumise riski.

DRASTIC-metoodika parandamiseks ja täpsemaks muutmiseks modifitseeriti mudeli kolme parameetrit, mis on mõjutatud kvaternaarisetetest. Esiteks muudeti põhjaveetaseme sügavuse parameetrit ehk D-parameetrit: muudetud versioonis võrreldakse põhjaveetaseme sügavust aluspõhja pealispinnaga. Muutus võimaldab kirjeldada piirkondi, kus põhjavee survetase on aluspõhja pealispinnast kõrgemal ja reoaine liikumine põhjaveekihti on raskendatud.

Lisaks muudeti veel kahte parameetrit, et kirjeldada konkreetselt kvaternaarisetete omadusi ja nende paksust. Varasem S-parameeter, mis algselt kirjeldas mulla omadusi, asendati pinnakatte tüübi parameetriga. Pinnakatte litoloogia määrab põhjavee kaitstuse otsesemalt kui ainult mulla omadused. Samuti muudeti I-parameetrit, mis varasema aeratsioonivööndi mõju kirjelduse asemel näitab pinnakatte paksust kui olulist tegurit, mis näitab kui pikk on reoaine teekond põhjaveekihini.

Töö raames täiendati põhjavee loodusliku kaitstuse hindamise meetodit inimtegevuse mõju arvestava maakasutuse parameetriga (DRASTIC-L meetod). Nii on võimalik siduda looduslik kaitstus tegelike reostusallikatega ning tulemuseks on realistlikum hinnang põhjavee reostumise riskile. Reostumise riski hinnates eristuvad näiteks põllumajanduspiirkonnad, mis on haavatavamad, samas kui metsaga kaetud aladel võib risk olla madalam isegi juhul, kui pinnakate on õhuke.

Muudetud DRASTIC metoodikat rakendati neljal uurimisalal: kolmel geoloogilise baaskaardi lehel (Järvakandi, Rapla ja Võru) ning Eesti-Läti piiriülesel alal. Need piirkonnad esindavad väga erinevaid geoloogilisi tingimusi. Järvakandi ja Rapla aladele on iseloomulik õhuke pinnakate ja karbonaatsetest kivimitest aluspõhi, mis muudab põhjavee tundlikumaks reostumise suhtes. Võru alal on pinnakatte setted paksemad ja aluspõhja moodustavad Devoni liivakivid, mis tagab parema põhjavee kaitstuse. Eesti-Läti uuringuala lisas piiriülese mõõtme, võimaldades hinnata metoodika rakendatavust ka erinevate riikide andmete põhjal.

Tulemuste valideerimiseks võrreldi põhjavee kaitstuse hinnangut Eesti senise metoodika alusel koostatud kaartidega ning viidi läbi tundlikkusanalüüs, mis näitas, millised parameetrid lõpptulemust enim mõjutasid. Analüüs kinnitas, et kõige olulisemad tegurid põhjavee kaitstuse kujunemisel on pinnakatte tüüp ja paksus. Modifitseeritud DRASTIC metoodika oli põhjavee kaitstust hindamiseks varasemast meetodist usaldusväärsem, praktilisem ja kiirem.

Eesti-Läti piiriülesel alal andis muudetud DRASTIC-metoodika häid tulemusi rahvusvahelises kontekstis. Meetodiga oli võimalik üheselt hinnata põhjavee kaitstust mõlemal pool piiri, kuid probleemid ilmnesid andmete kvaliteedi ja mõõtkava erinevuses kahe riigi vahel. Antud erinevused rõhutavad vajadust piiriülese andmekogumise ühtlustamise järele, et kaardistamise tulemused oleksid võrreldavad. Ilma ühtlustamiseta võivad tulemused näidata reaalsete hüdrogeoloogiliste tingimuste varieeruvuse asemel erinevuseid sisendandmetes.

Eesti-Läti piiriülesel alal hinnati lisaks põhjavee looduslikule kaitstusele ka reostumise riski DRASTIC-L meetodiga, millele on lisatud inimtegevuse mõju arvestav parameeter. Hinnang näitas, et looduslikult on hästi kaitstud alad võivad olla kõrgema reostuse riskiga, kui nende puhul on tegemist intensiivse maakasutuse, näiteks põllumajandusega. Samas, looduslikult vähem kaitstud, õhukese pinnakattega alad võivad olla madala reostumise riskiga, kui need asuvad metsades või poollooduslikel aladel.

Töö raames valideeriti põhjavee kaitstuse hinnangut põhjavee nitraadi sisaldusega, mis kinnitas küll korrelatsiooni põhjavee kaitstuse tasemega, kuid osutus pigem nõrgaks. Madalama korrelatsiooni põhjuseks on lausalise nitraadireostuse puudumine antud piirkondades ja üldine väga madal nitraadi looduslik tase Eesti põhjavees. Kuigi võrdlusega saadi täiendav kinnitus metoodika toimivuse kohta, võib siiski järeldada, et nitraadi sisaldusega võrdlemine ei pruugi olla meie oludes tõhusaim viis kaitstuse hinnangut valideerida.

Tulemuste põhjal võib järeldada, et uus muudetud DRASTIC meetod kirjeldab kaitstust täpsemini piirkondades, kus aluspõhjalise põhjaveekihi peal oleval kvaternaarisetted muudavad selle kohati surveliseks. Kirjeldatud hüdrogeoloogilised tingimused esinevad endistel jäätumisaladel üle Põhja-Euroopa ja Põhja-Ameerika. Töös välja töötatud parameetrite muudatused DRASTIC meetodile võimaldavad seda rakendada sellistes hüdrogeoloogilistes tingimustes ja saada täpsem põhjavee kaitstuse hinnang.

Eesti kontekstis pakuvad töö tulemused võrreldes varasemaga töökindlama ja praktilisema meetodi, et hinnata esimese aluspõhjalise põhjaveekihi kaitstust. Praegu kasutusel olev Eesti põhjavee kaitstuse hindamise meetod on välja töötatud 1980ndatel, on aeganõudev ning põhineb manuaalsel geoloogiliste kaartide tõlgendamisel. Uus muudetud DRASTIC meetod on GIS-i põhine meetod, millega saab põhjavee kaitstuse hinnangut anda kiirelt ning arvestades kohalikke hüdrogeoloogilisi omapärasid. Praeguse meetodi asendamine muudetud DRASTIC-uga võimaldaks Eesti põhjavee kaitstuse hindamist viia kooskõlla uuema teadusmetoodikaga.

Samuti ilmneb töö tulemustest, et maakasutuse info lisamine põhjavee kaitstuse hindamisse võimaldab täpsemalt kirjeldada põhjavee reostumise ohtu eri piirkondades. DRASTIC-L meetod annab hea võimaluse leidmaks kõige reostusohtlikumad alad: intensiivse maakasutusega alad, mis asuvad looduslikult kaitsmata põhjaveega aladel. Selliste alade leidmine võimaldab paremini planeerida põhjavee seiret ning anda sisendit maaplaneerimisse.

Muudetud DRASTIC ja DRASTIC-L meetodit saab rakendada ka seadusandluses, et muuta Eesti põhjavee kaitstusega seonduv seadusandlus teaduspõhisemaks ning lisada rakendusena põhjavee reaalse reostusohu hindamine. Samuti on need meetodid vajalikud abivahendid veemajanduskavade koostamiseks, et täita veepoliitika raamdirektiivi ja nitraadidirektiivi ning toetada seeläbi jätkusuutlikku põhjavee majandamist.

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Publikatsioonid:

Männik, M.; Bikše, J.; Karro, E.; Marandi, A. (2025). A framework for assessing groundwater vulnerability and pollution risk in transboundary aquifers: Insights from the Estonian-Latvian transboundary area. *Journal of Hydrology: Regional Studies*, 60. DOI: 10.1016/j.ejrh.2025.102525.

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