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Modified DRASTIC method for groundwater vulnerability assessment in areas with diverse Quaternary deposits

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ABSTRACT

The DRASTIC method is one of the most widely used groundwater vulnerability assessment techniques. In areas where the main useful aquifers are covered with an extra layer of diverse sediments, a further modification of the DRASTIC method is required for a more precise vulnerability estimation. In this article, the DRASTIC method was improved in areas characterized by a layer of diverse Quaternary deposits remarkably influencing the infiltration conditions. Three parameters were modified: (1) the D-parameter was adjusted to consider the overlying Quaternary deposits that, in some cases, make the aquifer confined, (2) the S-parameter was replaced by the Quaternary sediment-type parameter to assess the hydraulic characteristics of the highly variable deposits, and (3) the I-parameter was replaced by the thickness of the Quaternary deposits parameter to describe the distance from the ground surface to the main useful aquifer. The original and modified DRASTIC methodology was applied in an area with glacial sediments in Central Estonia. Comparing the results using the original and the modified DRASTIC method to a former Estonian groundwater vulnerability method showed that the DRASTIC method was significantly improved and could, thus, be successfully applied in other areas characterized by a heterogenous Quaternary sediment cover.

Key words: DRASTIC, groundwater protection, Quaternary cover, vulnerability mapping

HIGHLIGHTS

- Diverse Quaternary deposits require further modification to the DRASTIC method.
- D-, S-, and I-parameters were modified considering the complex hydrogeological conditions.
- A GIS model was created for an automatic mapping of groundwater vulnerability.
- The modified DRASTIC method shows significantly improved results compared to the original method.

INTRODUCTION

The protection of groundwater resources is of fundamental importance, as it is the most crucial drinking water resource in many areas of the world. However, water quality may be severely affected by urbanization and growth in industrial activities and agriculture. Therefore, identifying the most vulnerable areas to groundwater contamination is useful for environmental planning and decision-making (Gogu & Dassargues 2000). The level of natural groundwater protection is determined by the pathway from the origin of the potential contamination to groundwater (Zwahlen 2004). The vulnerability assessment primarily relies on the properties of soil, vadose zone, and the aquifer as several physical and chemical factors can affect the distribution and behavior of the pollutants (Vrba & Zaporozec 1994).

One of the most widely used groundwater vulnerability assessment techniques is the DRASTIC method developed by the US Environmental Protection Agency (Aller *et al.* 1987). The acronym DRASTIC refers to seven parameters used to determine groundwater vulnerability: *d*epth to water, net *r*echarge, *a*quifer media, *s*oil media, *t*opography, *i*mpact of the vadose zone, and hydraulic *c*onductivity (Aller *et al.* 1987). Several authors have applied the DRASTIC method to create vulnerability maps by using the original formula (Bera *et al.* 2021; Ahmed *et al.* 2022; Ouzerbane *et al.* 2022). The modification of the method, however, has improved the accuracy of the assessment of groundwater vulnerability (Maqsoom *et al.* 2021; Liu *et al.* 2022; Zhang *et al.* 2022). Therefore, many authors have increased the accuracy of the DRASTIC method in specific

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conditions by adding new parameters to the DRASTIC vulnerability index equation, e.g., fractured media parameter (Hamza *et al.* 2017), land use (Zhang *et al.* 2022), and anthropogenic influence (Albuquerque *et al.* 2021). The DRASTIC method has been used in various geological conditions around the world (Hamza *et al.* 2017; Kong *et al.* 2019; Albuquerque *et al.* 2021; Ouzerbane *et al.* 2022). However, the DRASTIC method has not been applied much in formerly glaciated areas in Europe, which have more complex (hydro)geological conditions due to the locally confining layer of heterogenous Quaternary sediments above the main useful (first bedrock) aquifer.

The need for modification of the DRASTIC method was raised from the first attempt to use the method in Estonia by Teiter (1995) who concluded that the method needs some improvement due to the highly variable Quaternary sediments on a local scale (Figure 1). In Estonia, the Quaternary deposits form, in many cases, a confining (e.g., a clayey moraine layer) layer covering the main useful aquifer, which sometimes, due to the groundwater regional flow conditions, has also a piezometric head above the ground level (artesian area, spring outflow, etc.). By the original DRASTIC method calculations, such areas would be qualified as unprotected, while they are, in reality, well protected due to the high hydraulic pressure in the main useful aquifer. Furthermore, the vulnerability of the main useful aquifer is directly influenced by the geological characteristics of the highly variable Quaternary deposits and their thickness (Koit *et al.* 2023).

The current Estonian groundwater vulnerability assessment method was specifically developed for local geological conditions (Estonian Land Board 2015). However, the method was developed for manual map-making in the pre-digital era and is time consuming. While the resulting vulnerability maps are reliable, there is a need to incorporate a more effective time-saving method. The original method is solely based on the characteristics of the Quaternary deposits, while the DRASTIC includes more hydrogeological parameters for groundwater vulnerability assessment. Considering the quickly evolving geographic information system (GIS) methods, groundwater vulnerability mapping can be further developed and automated to be less expensive, time saving, and simple to operate (Duarte *et al.* 2019). As the vulnerability mapping process is repeated for all map sheets, the process can be automated for more effective use of the method by including the same operations with GIS tools, which can be combined into a workflow (Duarte & Teododo 2016).

Therefore, in this article, we improve the vulnerability assessment using the DRASTIC method by modifying parameters affecting the vulnerability of the main useful aquifer due to the highly variable Quaternary deposits. Second, we use the QGIS Graphical Modeler to automate vulnerability mapping by creating a workflow, which takes as input all necessary

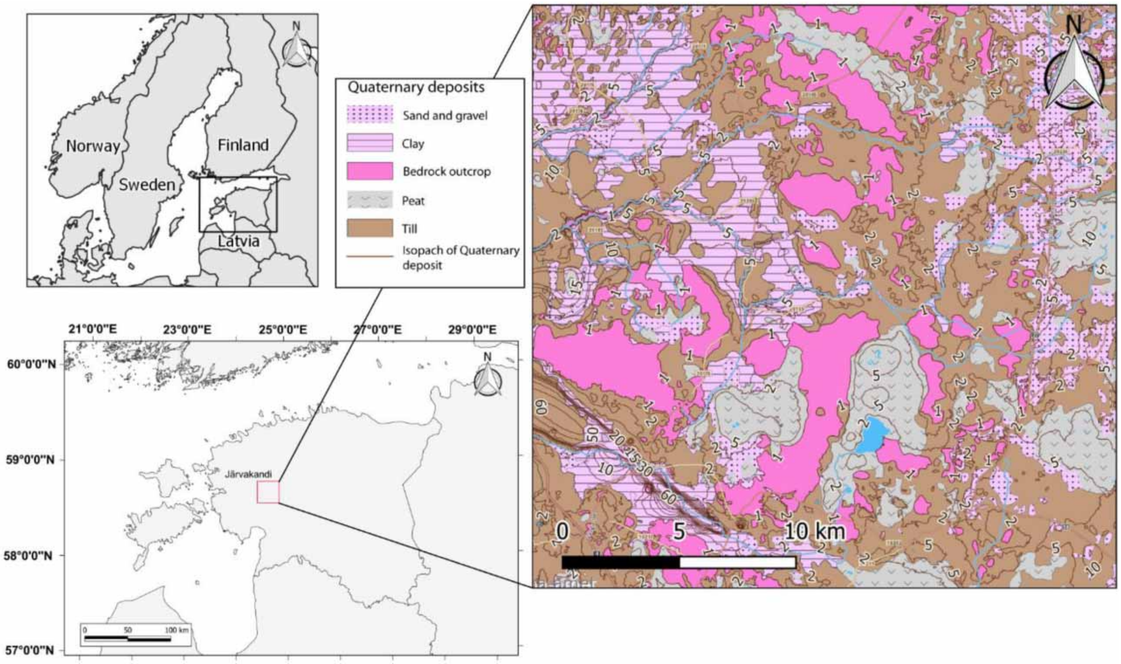

Figure 1 | Location of the Järvakandi study area in Estonia. Quaternary deposits in Järvakandi study area, data from Geological Survey of Estonia (2021). River and road data from Estonian Land Board (2021a).

files and creates a map using all parameters. Third, we compare the modified DRASTIC method to the previous vulnerability map produced by a methodology specifically developed for local geological conditions to validate the modification of the DRASTIC method.

MATERIALS AND METHODS

The study area

Estonia is situated in the northwestern part of the East-European Platform. Estonia's sedimentary cover consists of rocks of the Ediacaran, Cambrian, Ordovician, Silurian, and Devonian ages. The sedimentary rocks are overlain by the Quaternary deposits formed during the last glaciation period. Estonia's territory was freed from the continental ice between 15 and 13 ka BP (Kalm 2006), a time characterized by high activity of the glacial streams and lobes and highly variable glacial morphogenesis. Thus, glaciers left behind different landforms and deposits, up to 200 m thick, overlying the bedrock (Raukas 2009).

The Quaternary cover consists of different types of sediments by genesis, among which the most widespread are glacial moraine sediments, glaciolacustrine sands and clays and glaciofluvial sands, gravels, and pebbles. Along with those, alluvial sediments, which occur in river valleys, and sediments of bogs are present. The thickness of the Quaternary sediments varies from a couple of meters to, at its thickest, 100–200 m (Raukas & Kajak 1997).

In northern and central Estonia, the Quaternary deposits cover the first bedrock (main useful) aquifer formed by Ordovician and Silurian limestones and dolomites. The upper part of the formation is often karstified. In the southern and eastern parts of the country, the Devonian sandstones serve as the first bedrock aquifer (Perens & Vallner 1997).

The current study is performed in central Estonia (Figure 1) within the Järvakandi base map sheet (625 km^2). It is located between latitudes 58°38′ and 58°51′N and longitudes 24°25′ and 24°51′E. The elevation of the Järvakandi area is from 13 to 62 m above the sea level (m.a.s.l). The climate is moderately cool and humid, and the average annual precipitation is 500–750 mm. Net recharge varies from 10 to 30 mm/year (Vallner & Porman 2016). The first bedrock (main useful) aquifer in the study area is the Silurian–Ordovician aquifer system, which consists of limestones and dolomites. The piezometric head of the aquifer system varies from 15 to 55 m.a.s.l. The uppermost 30 m of the rock formation 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, the unconfined groundwater in highly cavernous limestones is weakly protected against surface pollution (Perens & Vallner 1997).

Järvakandi study area is suitable for testing the modified DRASTIC methodology as it comprises various types of Quaternary sediments. The main types are glacial sediments (tills) that cover 38% of the mapping area, glaciolacustrine clays that cover 15% of the area, and glaciofluvial sediments (sands and gravels) that cover 9.5%. The Quaternary layer is relatively thin, with a thickness predominantly below 5 m (Figure 1).

Description of the Estonian groundwater vulnerability assessment method

In Estonia, the bedrock aquifers composed of limestones and sandstones are relevant in the central water supply. Therefore, as a rule, only the vulnerability of the first bedrock aquifer is assessed. The groundwater vulnerability mapping in a scale of 1:50,000 started in the early 2000s when the compilation of geological base map by 625 km^2 map sheets was initiated. The vulnerability map is composed taking into account the five vulnerability classes defined according to the Estonian Water Act (Table 1), considering the properties and thickness of the Quaternary sediments. Currently, the geological map covers 34% of Estonian territory.

Description of the DRASTIC method

The US Environmental Protection Agency developed the DRASTIC method to assess groundwater vulnerability to contamination (Aller *et al.* 1987). The acronym DRASTIC refers to seven hydrogeological parameters used to determine groundwater vulnerability (Table 2): depth to water, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity (Aller *et al.* 1987).

Each parameter is classified either into ranges or into significant medium types based on the impact on pollution potential. The rating range is 1–10, where 1 means the lowest vulnerability and 10 the highest (Aller *et al.* 1987). All parameters have weights ranging from 1 to 5 to balance and enhance their importance (Aller *et al.* 1987). The vulnerability index is a weighted

Table 1 | Groundwater vulnerability areas according to the Estonian Water Act (Water Act 2022)

Vulnerability class	Description
Unprotected groundwater areas	Karst areas, alvars, and areas where the aquifer is covered by a moraine layer up to 2 m thick or a sand or gravel layer up to 20 m thick
Weakly protected groundwater areas	The aquifer is covered by a moraine layer 2–10 m thick or a clay or loam layer up to 2 m thick, or a sand or gravel layer 20–40 m thick
Groundwater areas of medium protection	The aquifer is covered by a moraine layer 10–20 m thick or a clay or loam layer 2–5 m thick
Relatively protected groundwater areas	The aquifer is covered by a moraine layer more than 20 m thick or a clay or loam layer more than 5 m thick
Protected groundwater areas	The aquifer is covered by a regional aquitard

Table 2 | DRASTIC method parameters (O – original, M – modified), descriptions, and weights

Parameter	Original/ modified	Description	Weight
Depth to water (D)	O	Refers to the depth from the ground surface to the water table. A deeper water table means a lower contamination risk	5
	M	Depth of the piezometric head compared to the bedrock surface. Contamination risk is lower in areas where the piezometric head is above the bedrock surface and higher in areas where it is below the bedrock surface	5
Net recharge (R)	O	Represents the amount of water that infiltrates through the ground surface and the vadose zone and reaches the water table. Recharging water facilitates the transportation of contaminants to the aquifer. A higher recharge value indicates a more significant potential for groundwater contamination	4
Aquifer media (A)	O	Refers to 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/Quaternary sediment type (S)	O	Refers to the uppermost weathered part of the vadose zone and determines the amount of water that can infiltrate into the ground. The presence of clays and organic material can limit contaminant migration	2
	M	Refers to the characteristics of the Quaternary sediments above the main useful aquifer, which determine the amount of water that can infiltrate into the ground	5
Topography (T)	O	Refers to the slope of the land surface. 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/ impact of the vadose zone (I)	O	Refers to the unsaturated zone above the water table, and the sediments' type determines the attenuation of the contaminants. Higher permeability allows faster contaminant movement	5
	M	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)	O	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

sum of the seven parameters (Gogu & Dassargues 2000):

$$D_i = \sum_{J=1}^{7} (W_j \times R_j) \tag{1}$$

where D_i is the vulnerability index for a mapping unit, W_j is the weight of parameter j, and R_j is the rating of parameter j. A higher vulnerability index refers to a greater groundwater contamination risk.

Groundwater vulnerability estimation is based on vulnerability indexes, which are divided into classes according to their values. Many authors have divided the result into five groundwater vulnerability classes with equal intervals (Huan *et al.* 2012; Barzegar *et al.* 2019; Kadkhodaie *et al.* 2019). Hamza *et al.* (2015) suggest dividing 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).

The modification of the DRASTIC method

The original DRASTIC method was applied in Estonia within the Järvakandi geologic map sheet (Figure 1), where the main aquifer used for the groundwater supply consists of carbonate rocks. However, in regions with a complex Quaternary cover, the original DRASTIC method overestimates the vulnerability of areas with groundwater overflow and regions where groundwater is occasionally confined. The method also 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. The heterogeneous nature of the Quaternary sediments leads to water quality issues (Koit *et al.* 2023), and therefore, there is a need for a more precise vulnerability estimation.

To increase the accuracy of vulnerability maps in areas with Quaternary deposits, the parameters of the DRASTIC method, which are affected by the local geological features, need to be modified. Therefore, three parameters of the DRASTIC method were modified: the depth to water (D) parameter, the soil type (S) parameter, and the impact of the vadose zone (I) parameter. The original, as well as the modified parameters and their weights, are given in Table 2, and the ranges and ratings for each parameter are shown in Table 3. The net recharge (R), aquifer media (A), topography (T), and hydraulic conductivity (C) parameters were not changed as they are universal and not directly affected by the specific local geological conditions.

Initially, the depth to water parameter allowed for assessing the distance from the ground surface to the aquifer (Aller *et al.* 1987). The deeper the water table, the lower the contamination risk. The water table near the ground surface receives the highest vulnerability rating. In Estonia, the main useful aquifers are overlain by Quaternary sediments making the aquifers, in some cases, confined. Therefore, the D-parameter needs to be modified to describe situations where the water table of the main useful aquifer marks a confined aquifer's piezometric surface.

Consequently, the water table is, as an alternative, compared to the bedrock surface in the modified DRASTIC method. 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 D-parameter is lower in areas where the piezometric head is above the bedrock surface and higher in areas where it is below the bedrock surface. The ranges for assessing the depth to water parameter considering the depth from the piezometric head to the bedrock surface are shown in Table 3.

In addition to this, considering the importance of the Quaternary sediment types to the vulnerability of the main useful aquifer and their correlation with soil types, the S-parameter was replaced by the Quaternary sediment-type parameter (Table 2) to assess the geological characteristics of the deposits. The new parameter was assigned a new weight of 5 to emphasize its importance, as opposed to the former weight of 2.

The vadose zone for the main useful aquifer is formed by the Quaternary deposits. The properties of the sediments and their impact on the vulnerability were described in the Quaternary sediment-type (S) parameter. Therefore, the original impact of the vadose zone parameter was replaced by the thickness of the Quaternary sediment-type parameter (Table 2) to describe the path of the pollutant from the ground surface to the main useful aquifer, as it directly influences the vulnerability. The ranges for assessing the thickness of the Quaternary sediments are shown in Table 3.

The modified DRASTIC method can be applied to assess the intrinsic vulnerability of the main useful aquifer with an overlying vadose zone of Quaternary deposits using Equation (2):

$$D_i = D \times 5 + R \times 4 + A \times 3 + S \times 5 + T \times 1 + I \times 5 + C \times 3 \tag{2}$$

Table 3 | Original (Aller *et al.* 1987) and modified DRASTIC parameters

(D) Depth to water (original)		(D) Depth to water (modified)		(R) Net recharge (original)		(A) Aquifer media (original)		(S) Soil media (original)	
Range (m)	**Rating**	**Depth of the piezometric head compared to the bedrock surface[a] (m)**	**Rating**	**Range (mm/y)**	**Rating**	**Type**	**Rating**	**Type**	**Rating**
0–1.5	10	<− 10	10	0–50	1	Massive shale	1–3	Thin or absent	10
1.5–5	9	−10 to −5	9	50–100	3	Metamorphic/igneous	2–5	Gravel	10
5–10	7	−5 to −1	7	100–175	6	Weathered metamorphic/igneous	3–5	Sand	9
10–15	5	−1 to 0	6	175–250	8	Glacial till	4–6	Peat	8
15–20	3	0 to 1	5	>250	9	Bedded sandstone, limestone	5–9	Shrinking clay	7
20–30	2	1 to 3	3			Massive sandstone	4–9	Sandy loam	6
>30	1	3 to 5	2			Massive limestone	4–9	Loam	5
		>5	1			Sand and gravel	4–9	Silty loam	4
						Basalt	2–10	Clay loam	3
						Karst limestone	9–10	Muck	2
								No shrinking clay	1

(S) Quaternary sediment type (modified)		(T) Topography (original)		(I) Impact of the vadose zone (original)		(I) Thickness of the Quaternary sediments (modified)		(C) Hydraulic conductivity (original)	
Type	**Rating**	**Slope (%)**	**Rating**	**Type**	**Rating**	**Range (m)**	**Rating**	**Range (m/d)**	**Rating**
Clay	1	0–2	10	Confining layer	1	0–2	10	0.04–4	1
Gyttja	2	2–6	9	Silt/clay	3	2–5	9	4–12	2
Silt	6	6–12	5	Shale	3	5–10	7	12–28	4
Peat	6	12–18	3	Limestone	6	10–20	5	28–40	6
Till	7	>18	1	Sandstone	6	20–40	3	40–80	8
Fine sand, coarse sand, gravel	8			Bedded limestone, sandstone	6	>40	1	>80	10
Cobbles, boulders	9			Sand, gravel with silt, clay	6				
Bedrock outcrop	10			Metamorphic/igneous	4				
Karst field	10			Sand and gravel	8				
				Basalt	9				
				Karst limestone	10				

[a] Negative values indicate a piezometric head below the bedrock surface.

where D_i is the vulnerability index of a mapping unit, D is the depth to groundwater, R is the net recharge, A is the aquifer media, S is the Quaternary sediment type, T is the topography, I is the thickness of the quaternary sediments, and C is the hydraulic conductivity.

Data sources

The data used for the groundwater vulnerability analysis are presented in Table 4. 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.

Table 4 | Data sources of the DRASTIC parameters

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

Automating the mapping process and defining vulnerability classes

The groundwater vulnerability mapping procedure was carried out using the QGIS software. The QGIS graphical modeler allows to create complex workflow models to make a chain of GIS operations for an automatic workflow of the groundwater vulnerability mapping process (Duarte & Teododo 2016). The QGIS model can be executed as a single algorithm making it considerably less time demanding. The created model contains all necessary processes for creating layers for all parameters using data from the sources shown in Table 4.

Raster layers of all seven parameters were created to generate the final DRASTIC map. For the calculation of the D-parameter, the raster file of the piezometric surface was interpolated using the isolines of the groundwater head (Geological Survey of Estonia 2021). From the piezometric head, the raster file of the bedrock surface was subtracted. A negative value means the water level is below the bedrock surface and is given a higher vulnerability rating according to the ranges in Table 3. A positive value is above the bedrock surface and given a lower vulnerability rating.

The slope of the land for the T-parameter was calculated from the digital elevation model (DEM) of the land surface (Estonian Land Board 2021a). To assess the thickness of the Quaternary sediment-type (I) parameter, a raster layer was interpolated using the isolines of the thickness of the Quaternary deposits (Geological Survey of Estonia 2021). The C-parameter (hydraulic conductivity) assessment was conducted based on average hydraulic conductivity values in Estonia, published by Perens & Vallner (1997). Hydraulic conductivity of 5–10, 2–6, and 10–50 m/d was used for Quaternary sediments, sandstones, and carbonate rocks, respectively.

In the GIS model, all parameters were assigned a vulnerability rating according to Table 3. In addition, parameters, which were vector layers (net recharge, aquifer media, Quaternary sediment type, hydraulic conductivity), were converted into raster layers with a resolution of 80 m × 80 m. The resulting raster layers were multiplied by their weights using Equation (2) to find the vulnerability index (D_i) values.

The final vulnerability index (D_i) values generated using the modified DRASTIC method ranged from 78 to 213. These values were divided into five quantile classes (Table 5), as suggested by Hamza *et al.* (2015) and taking into account the local regulation for groundwater vulnerability assessment defined in the Estonian Water Act (2022). Hamza *et al.* (2015)

Table 5 | Vulnerability index (D_i) values divided into five classes

	Percentage of the D_i range (78–213)	D_i values
Well protected	0–10.00	78–91.5
Relatively well protected	10.00–28.99	91.5–117.15
Moderately protected	29.00–46.99	117.15–141.45
Weakly protected	47.00–64.99	141.45–165.75
Unprotected	65.00–100	165.75–213

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%). 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% (Table 6).

Sensitivity analysis

Sensitivity analysis evaluates the contribution of the input parameters to the analytical model’s output. This technique is helpful for the validation of the result and for accurate interpretation of the groundwater vulnerability maps (Gogu & Dassargues 2000). Two types of sensitivity analysis can be conducted to assess the effectiveness of weights and ratings: map-removal sensitivity analysis proposed by Lodwick *et al.* (1990) and the single-parameter sensitivity analysis introduced by Napolitano & Fabbri (1996).

Single-parameter sensitivity analysis compares the ‘real’ or ‘effective’ weight of each parameter in the study area to the theoretical weight assigned by the DRASTIC method. The effective weight (W_{pi}) was calculated for each pixel of the map and computed in Equation (3):

$$W_{\mathrm{pi}} = \frac{P_{\mathrm{Ri}} P_{\mathrm{Wi}}}{D_i} \times 100 \tag{3}$$

where P_{Ri} and P_{Wi} are the ratings and the weights of the parameter P assigned to the pixel i, and D_i is the vulnerability index as computed in Equation (1). The single-parameter analysis examines the impact of each parameter on the overall vulnerability index.

Map-removal sensitivity analysis defines the sensitivity of the vulnerability map when one or more parameters are removed from the analysis (Lodwick *et al.* 1990). The sensitivity measure S of a parameter is calculated in Equation (4):

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

where V is the unperturbed vulnerability index and V' is the perturbed index, and N and n are the numbers of parameters used to calculate V and V', respectively. The unperturbed vulnerability index is obtained using all seven parameters, while the perturbed one is computed using a smaller number of parameters.

Table 6 | Results from the map-removal sensitivity analysis (parameter removed)

	Variation index (%)			
Parameter removed	**Mean**	**Standard deviation**	**Minimum**	**Maximum**
D	0.87	0.74	0.00	11.55
R	1.96	0.07	1.49	2.07
A	0.56	0.50	0.00	3.72
S	1.34	0.50	0.00	3.92
T	1.34	0.18	0.30	2.30
I	2.44	0.55	0.09	4.56
C	0.29	0.34	0.00	2.95

RESULTS

The map generated using the new modified DRASTIC method was compared to the map made using the methodology for assessing the vulnerability of the main useful aquifer, specifically developed taking into account the Estonian geological conditions. In addition, the map was compared to a map generated using the original DRASTIC method developed by Aller *et al.* (1987).

Comparing groundwater vulnerability maps of the Järvakandi study area prepared by different methodologies shows variation in maps generated using the original (Figure 2(a)) and modified (Figure 2(b)) DRASTIC parameters. The original method does not distinguish any well-protected or relatively well-protected areas. The moderately protected area forms 13% of the study area, being represented by clay sediments. More than half (58%) of the area, where peat and till are the dominating sediment types, is weakly protected. Unprotected territories cover 28% of the study area and coincide mostly with bedrock outcrops.

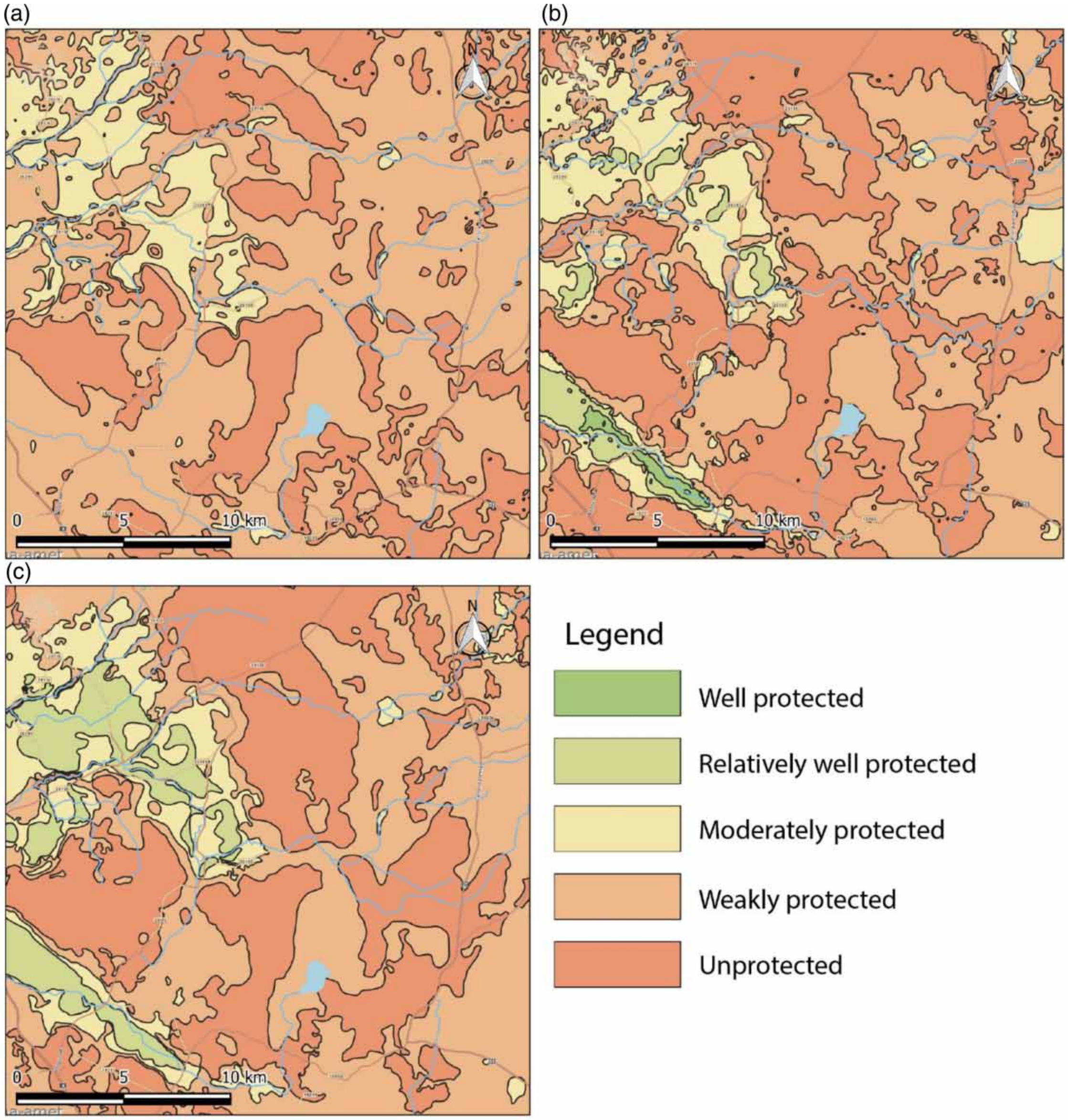

Figure 2 | Groundwater vulnerability maps of the Järvakandi study area. (a) Map generated using original DRASTIC method parameters. (b) Map generated using modified DRASTIC method parameters. (c) Map completed using Estonian groundwater vulnerability assessment method (Estonian Land Board 2015). River and road data from Estonian Land Board (2021b).

In the groundwater vulnerability map of the study area composed using the modified DRASTIC method (Figure 2(b)), relatively well-protected and well-protected areas cover 2% of the map area. These areas have a thick Quaternary sediment cover (more than 15 m) covering the main useful aquifer. Moderately protected areas (2–5 m thick clay layer) cover 14% of the Järvakandi map sheet. Weakly protected areas with 2–10 m thick till layers and peat layers occupy 42% of the map sheet. Unprotected areas with a thin (less than 2 m) Quaternary sediment cover also cover 42% of the study area.

The third version of the groundwater vulnerability map sheet (Figure 2(c)) was prepared using the former method of vulnerability mapping developed to assess groundwater vulnerability in Estonia by using only the thickness and the type of the Quaternary deposits. Unprotected areas cover 37% of the map area, while weakly protected areas cover 44% of the study area. Moderately protected areas cover 11% and relatively well-protected area covers 7%. Well-protected areas are regional aquitards, which are not present in the current study area.

The results of modifying the depth to water (D) parameter are shown in Figure 3. The original values of the D-parameter evaluate the areas of artesian flow and areas with water level substantially higher than the bedrock surface as unprotected areas (Figure 3(a)). The modified D-parameter values (Figure 3(b)), however, recognize the areas of artesian flow as protected areas and evaluate the areas with water level lower than the bedrock surface as more unprotected.

Sensitivity of the DRASTIC model

The statistical summary of the seven parameters used to calculate the groundwater vulnerability index using the modified DRASTIC method is given in Table 7. The highest risk of groundwater contamination in the study area originated from the topography (T), the thickness of the Quaternary sediments' layer (I), and the aquifer media (A) parameters, with mean

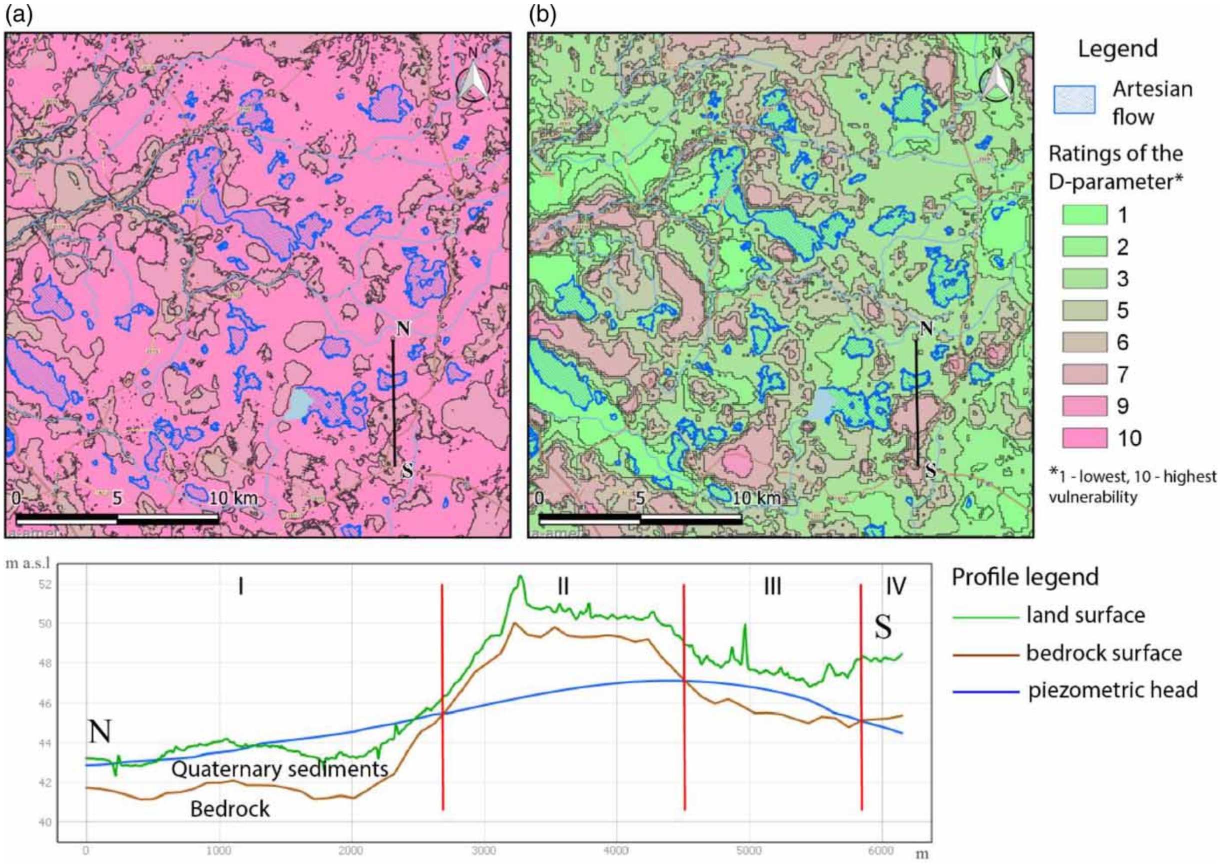

Figure 3 | The modification of the D-parameter. (a) Ratings of the original D-parameter, where deeper water level means lower vulnerability. (b) Ratings of the modified D-parameter, which compares the piezometric surface with the bedrock surface. The profile N-S shows areas where the vulnerability of 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.

Table 7 | Statistical summary of the parameters on the modified DRASTIC map

Value	D	R	A	S	T	I	C
Minimum	1	1	9	1	1	1	8
Maximum	9	1	10	10	10	10	8
Mean	3.5	1	9.3	6.4	9.9	9.3	8
Standard deviation	1.8	0	0.5	2.7	0.6	1.4	0
Coefficient of variation (%)	50.3	0	4.9	41.8	6.3	14.6	0

values of 9.9, 9.3, and 9.3, respectively. The Quaternary sediment-type (S) and the depth to water (D) parameters have a lower contribution to the vulnerability of the study area, with mean values of 6.4 and 3.5.

The analysis of the coefficient of variation indicates that the highest contribution to the variation of the DRASTIC vulnerability index is caused by the depth to water (D) parameter (50.3%), which illustrates the importance of modifying the parameter to accurately assess the vulnerability in complex areas, where the water table could make the aquifer confined. The second highest contribution is by the Quaternary sediment-type (S) parameter (41.8%), which is due to the high variability of the Quaternary sediment types in the study area. The thickness of the Quaternary sediment-type (I) parameter (14.6%), the topography (T) parameter (6.3%), and the aquifer media (A) parameter (4.9%) have a lower contribution to the variation of the DRASTIC index. The net recharge (R) and hydraulic conductivity (C) parameters have no variability due to a small study area and the low density of data available in Estonia.

Single-parameter sensitivity analysis

Single-parameter sensitivity analysis was performed to compare each parameter's 'real' or 'effective' weight in the study area to the theoretical weight assigned by the modified DRASTIC method. The effective weight was computed using Equation (3), and the theoretical weight of a parameter was calculated based on the weights in Equation (4). Table 8 shows the theoretical weight assigned by the method, the average effective weight computed on all map pixels, the standard deviation, and the minimum and maximum values.

The effective weights showed some deviation from the theoretical weight. According to the single-parameter analysis conducted within this study, the parameters with the highest weights contributing to the vulnerability assessment are the thickness of the Quaternary (I) parameter (28.7%) and the Quaternary type (S) parameter (19.3%), which illustrates the importance of including the properties of the Quaternary deposits to the DRASTIC calculation. Factors with a higher effective weight also highlight the importance of obtaining precise and accurate information about them. The effective weight of the D-parameter (10.6%) on the final vulnerability index is lower than the theoretical (19.2%), proving the presence of areas with a piezometric head above the bedrock surface, making the aquifer confined and, therefore, protected against contamination. The weight of the net recharge R-parameter is much less (average weight of 2.5%) compared to the theoretical weight (15.4%) due to the small-scale net recharge map causing a low variability of the net recharge value in the Järvakandi study area.

Table 8 | Results of the single-parameter sensitivity analysis

		Effective weight (%)			
Parameter	Theoretical weight (%)	Average weight (%)	Standard deviation (%)	Minimum value (%)	Maximum value (%)
D	19.2	10.6	4.2	1.6	24.1
R	15.4	2.5	0.4	1.9	5.1
A	11.5	17.6	3.0	12.9	36.1
S	19.2	19.3	6.4	3.1	32.3
T	3.8	6.2	1.2	0.6	12.5
I	19.2	28.7	3.8	4.5	40.0
C	11.5	15.1	2.4	11.3	30.7

Map-removal sensitivity analysis

The results of the map-removal sensitivity analysis were calculated by removing one input parameter layer at a time from the output of using the modified DRASTIC method for each of the cell in the map grid. Table 6 presents the variation of the vulnerability index as a result of removing one parameter at a time. The highest variation of the vulnerability index occurs when removing the thickness of the Quaternary sediments' layer (I) parameter (2.44%). This is due to a high contamination risk (mean rating 9.3, Table 7) in the relatively thin Quaternary layer in Järvakandi area. In addition, the vulnerability index is sensitive to the removal of the net recharge (R) parameter in Järvakandi due to low net infiltration values (mean rating 1, Table 7) contributing to a higher pollution risk. Removal of Quaternary sediment-type (S) parameter and topography (T) can also contribute significantly to the change of the vulnerability index. The results indicate the importance of the parameters describing the properties of the Quaternary sediments above the aquifer. According to the results of the map-removal analysis of one parameter at a time, the parameters with the lowest variation were excluded one by one (Table 9). Removing one or more parameters results in inconsistent results, which indicate that all seven parameters are important to receive a precise vulnerability assessment.

DISCUSSION

The main aim of this article was to achieve a more precise vulnerability estimation in areas with a highly variable Quaternary cover above the main useful aquifer by improving the DRASTIC method. Due to the heterogeneous nature of the Quaternary sediments that lead to water quality issues (Koit *et al.* 2023), there is a need for a more precise vulnerability estimation to find areas most vulnerable to pollution. Moreover, the current method for groundwater vulnerability mapping in Estonia is a time-consuming manual map-making method developed in the pre-digital era. An improved vulnerability assessment method leads to better water management by lowering the pollution risk. For this, 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 using the DRASTIC method.

According to the results of the groundwater vulnerability maps obtained by both the original and modified DRASTIC methodology, the modification shows improvement by having significantly more similarities to the former Estonian groundwater vulnerability mapping method. The modified map (Figure 2(b)) contains relatively well- and well-protected areas (2%), while there are none on the original method map (Figure 2(a)), but 7% on the map by the former Estonian method (Figure 2(c)). In addition, the unprotected areas are more prevalent on the modified (42%) than on the original (28%) DRASTIC method map, while they are also more prevalent on the Estonian method map (37%).

Replacing the original D-parameter with a parameter comparing the piezometric surface with the bedrock surface enables assessing the groundwater vulnerability taking into account the overlying Quaternary cover, which in many cases acts as an aquitard. When the piezometric head is above the bedrock surface, the aquifer acts as confined, and the pollutant movement to the aquifer is hindered. Thus, the new approach allows assessing areas of artesian flow as more protected areas and areas with water level lower than the bedrock surface as more unprotected, improving the outcome significantly (Figure 3).

The replacement of the original impact of the vadose zone (I) parameter with the thickness of the Quaternary sediments enabled to assess a crucial parameter that directly influences the vulnerability of the first aquifer by describing the path of the pollutant from the ground surface to the water table. For example, the new I-parameter improved the vulnerability assessment

Table 9 | Results of the map-removal sensitivity analysis (parameters used)

	Variation index (%)			
Parameters used	**Mean**	**Standard deviation**	**Minimum**	**Maximum**
D, R, A, S, T, I	0.29	0.34	0.00	2.95
D, R, S, T, I	0.95	1.01	0.00	7.89
R, S, T, I	0.92	0.88	0.00	7.95
R, T, I	2.01	1.09	0.00	9.24
R, I	1.80	1.64	0.00	10.54
I	8.53	0.80	5.95	13.45

in the southwest part of the study area, where the Quaternary deposits are up to 60 m thick (Figure 1), making the aquifer considerably more protected. On the original map, these areas are weakly protected (Figure 2(a)), while the modified method shows relatively well-protected areas.

Another crucial aspect of assessing the vulnerability of the formerly glaciated areas with a more complex hydrogeology, the new Quaternary sediment-type (S) parameter, was added to the DRASTIC method by replacing the soil media (S) parameter. The new weight of 5 enabled to emphasize the importance of the impact of the Quaternary cover above the main useful aquifer. For example, 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 in the map created using the modified method, where these areas are marked as relatively well protected.

Developing a workflow model in the QGIS Graphical Modeler enabled the creation of a vulnerability map to be more effective and allows updating of the map when new information becomes available. The QGIS workflow model is developed to work specifically with the Estonian geological base map geodatabase and contains all necessary processes for creating a vulnerability map using the modified DRASTIC method.

CONCLUSION

In this article, the DRASTIC method was applied in formerly glaciated areas with a Quaternary cover consisting of various sediment types. The Quaternary deposits, which overlie the main aquifers, remarkably influence the infiltration conditions. Thus, the correct estimation of groundwater vulnerability requires the modification of the original DRASTIC parameters. The DRASTIC method has not been applied in European formerly glaciated areas and modified to consider the specific Quaternary cover making the current methodology novel in this region.

In the current study, 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. A groundwater vulnerability map of the Järvakandi study area was generated by applying the modified DRASTIC methodology using a model created with the QGIS Graphical Modeler. The vulnerability index (D_i) values ranged from 78 to 213. In the groundwater vulnerability map generated using the modified DRASTIC methodology, relatively well-protected area covers 2% of the map area, moderately protected area 14%, weakly protected areas 42%, and unprotected area also covers 42% of the study area. According to the sensitivity analysis conducted within this study, the highest contributors to the vulnerability assessment are the thickness of the Quaternary (I) parameter and the Quaternary sediment-type (S) parameter, which illustrates the importance of including the properties of the Quaternary deposits to the DRASTIC calculation.

Comparing the results of the vulnerability assessment using the original and the modified DRASTIC to a former Estonian groundwater vulnerability method showed that the DRASTIC method was significantly improved by modifying the depth to water (D), soil properties (S), and impact of the vadose zone (I) parameters. Thus, the modified method could also be applicable in other areas characterized by a heterogenous Quaternary sediment cover above the main useful aquifer.

AUTHORS' CONTRIBUTION

Magdaleena Männik: conceptualization, methodology, software, writing – original draft, visualization, writing – review and editing; Enn Karro: supervision, writing – review and editing; Andres Marandi: supervision, conceptualization; Maile Polikarpus: methodology, software; Tavo Ani: methodology, software; Alar Rosentau: supervision, writing – review and editing.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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