

Evaluation of intrinsic vulnerability to nitrate contamination of groundwater: appropriate fertilizer application management

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Abstract In agricultural areas, fertilizer application is the main source of nitrate contamination of groundwater. To develop fertilizer management strategies to combat this problem, arable land in Hokkaido, Japan was evaluated using geographic information system techniques for intrinsic groundwater vulnerability to nitrate contamination. The DRASTIC method was modified to adapt it to the Hokkaido environment and used for the evaluation. Of the seven original DRASTIC factors, the depth to water (D), net recharge (R), soil media (S), topography (T), and impact of vadose zone media (I) were selected and used to explain the vertical movement of contaminants to the aquifer. The rating for the net recharge factor was also modified to a dilution factor for contaminants, rather than as a transporter. The frequency of wells with nitrate concentrations exceeding the Japanese environmental standard (10 mg/L) was reasonably explained by vulnerability evaluation results (GLM: logit-link, quasi-binomial distribution, $Y = [1 + \exp(6.873765 - 0.045988 \times X)]^{-1}$, $p < 0.001$). However, in the paddy fields and pastures, vulnerability did not exhibit a clear relationship with the frequency of wells exceeding the standard. This suggests that the modified DRASTIC method is applicable for fertilizer application management in upland fields. In addition, under the ongoing policy for acreage allotment for rice production, this method will be useful for deciding the arrangement of arable land and crop rotation taking into

consideration the potential risk of fertilizer-induced nitrate contamination of groundwater.

Keywords Groundwater · Nitrate contamination · Fertilizer application · GIS · Hydrogeology · DRASTIC

Introduction

Problems of nitrate contamination of groundwater

Protecting groundwater as a drinking water resource is an important issue in Hokkaido, Japan. In particular, nitrate and nitrite (NO_x-N) contamination has been reported recently; the local government is trying to tackle this problem (Hokkaido Government 2005). In infant bodies, the nitrate taken in through drinking water is reduced to nitrite. The hemoglobin in blood is oxidized by nitrite into methemoglobin, which cannot transport oxygen. This leads to cyanosis symptoms (Fawns and Aldridge 1954); this disorder is called methemoglobinemia and is widely known as the blue-baby syndrome. There have been episodic though rare reports of methemoglobinemia in Japan (Tanaka et al. 1996). In Japan, the environmental standard for the combined concentration of nitrate and nitrite in groundwater was set to 10 mg/L in 1999 during the revision of the Environmental Quality Standards for Groundwater Pollution, which is based on the Basic Environment Law. In Hokkaido, 13% of the water in waterworks is supplied through on groundwater or springs. However, for small waterworks providing water to fewer than 5,000 people, the groundwater dependency increases to 35%. Out of the 180 cities in Hokkaido Prefecture, 136 have small waterworks providing either total or partial coverage. In addition, private wells are still being utilized in rural areas

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for multiple uses, including residential water for drinking or livestock. Thus, in Hokkaido, groundwater conservation is an issue that must be dealt with for citizens' healthcare. Methemoglobinemia is known to be pathogenic to livestock as well (Campbell et al. 1954). Nitrate has also been reported to have a negative effect on the survival rate of wildlife such as salmonid fish fry (Kincheloe et al. 1979) and the growth rate of the common frog (*Rana temporaria*) (Johansson et al. 2001), amphipod (*Eulimnogammarus toletanus* and *Echinogammarus echinosetosus*) (Camargo et al. 2005), and caddisfly (*Hydropsyche occidentalis*, *Cheumatopsyche pettiti*, and *Hydropsyche exocellata*) (Camargo et al. 2005). These examples suggest that nitrate contamination of water is an important environmental problem worldwide.

Nitrate sources in groundwater

The main nitrate sources in groundwater are fertilizer applications on cultivated land, manure from livestock, and factory and domestic wastewater. Tase (1992) reported that the main sources of nitrate in groundwater were fertilizer and manure. Legal controls were imposed on manure from livestock barns by the Law on Promoting Proper Management and Use of Livestock Excreta in 1999. Factory and household wastewater is regulated by the revised of limits specified in the Water Pollution Control Law and the prohibition of newly established single-type private sewage treatment tanks in 2001. In addition, the number of sewage systems has been rapidly increasing (88.4% in March 2008) in Hokkaido (Hokkaido Government 2008). These legal regulations are helping to reduce the wastewater and manure contributions to nitrate contamination of groundwater. In contrast, contaminated water drained from fertilized cultivated land is difficult to control. Control measures, excluding appropriate fertilizer application, such as breaking the plow layer for efficient absorption of nitrates by root systems (Higashida and Yamagami 2003) and growing cover crops (Meisinger et al. 1991) have been reported. However, cost effectiveness is the major obstacle in the implementation of these measures. Therefore, nutrient management and optimal regional planning for different types of crops characteristic to the local environment are required to minimize the tradeoff between nitrate load reduction in groundwater and sustainable food production. Further, evaluation of the intrinsic vulnerability of groundwater to contamination is essential for managing these issues.

DRASTIC and a brief review of its modifications

DRASTIC (Aller et al. 1987), which was developed by United States Environmental Protection Agency (EPA), is

the most widely used method for groundwater vulnerability evaluation (Thirumalaivasan et al. 2003; El Naqa 2004; Seabra et al. 2009). Following the principles of DRASTIC, many studies have made modifications for specific areas of interest. These modifications are the issue for scientific study and potential vulnerability evaluation (Seabra et al. 2009). Studies have tried to calibrate the DRASTIC rating system with surveys on the actual quality of water from wells (Rupert 2001; Panagopoulos et al. 2006). In response to specific requirements, attempts have been made to extract and use only the required or available factors from the seven original DRASTIC factors (Fritch et al. 2000). In some studies, new factors related to nitrogen input, such as land use or vegetation factors were added to the original factors (Al-Adamat et al. 2003). In addition, there was a study integrating DRASTIC and new parameters into SINTACS (Civita and De Maio 1998) to suit the Mediterranean area. Flexibility to modification is one of the most distinctive and superior features of DRASTIC.

Necessary modifications of DRASTIC to adapt Hokkaido region

The precipitation over 70% of the land in USA is less than 1,000 mm/year (average of 1961–1990; Daly and Taylor 2000). In the original DRASTIC method used for calculation, the maximum recharge rate is set as 254 mm/year (10 in/year). These facts suggest that DRASTIC was developed on the assumption that it would be used in arid or semi-arid areas where surface water availability is not enough. In addition, flat areas suitable for residential areas or arable land which are the focus of DRASTIC, consist of not only alluvial but also structural plains. However, Hokkaido is relatively humid with an average annual precipitation of more than 1,000 mm. Hokkaido is also located in an area with high mountain-building activity with many volcanoes. These climatic and geographical conditions result in high degradation and deposition rates. Therefore, in Hokkaido, alluvial plains dominate the flat areas, and terraced upland originating from fluvial or quaternary volcanic deposits (e.g., pyroclastic flow deposits or volcanic ash) is widely distributed. Because of this, Hokkaido has different environmental characteristics in terms of climate and hydrogeological conditions, as compared to previously reported DRASTIC study areas. Therefore, modification is required to adapt DRASTIC to Hokkaido.

Goal of this study

In order to conserve groundwater quality in agricultural areas, it is necessary (1) to ensure that fertilizer application is appropriate to the local environment and (2) to have a cost-effective spatial arrangement of measures intended to

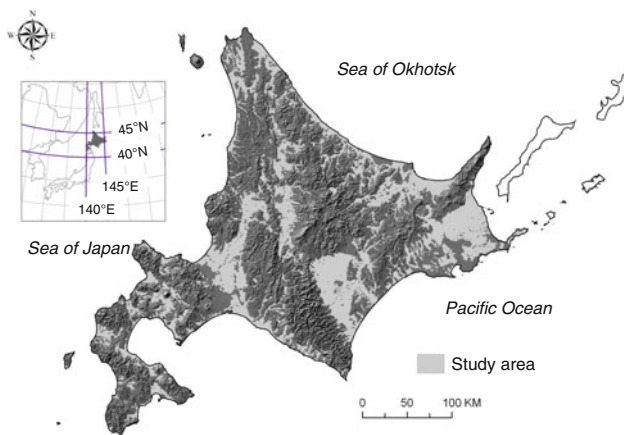


Fig. 1 Study area

reduce the nitrate loading. To realize these goals, the intrinsic vulnerability of various types of lands to nitrate contamination of groundwater was evaluated as a criterion in this study. The original DRASTIC method was modified for the evaluation by eliminating two factors and changing the rating system. The correlation between the calculated vulnerability and the groundwater quality from wells was examined to validate this evaluation.

Materials and methods

Site description

The study area is shown in Fig. 1. Hokkaido is the northernmost main island of Japan. As the study area, an area whose agricultural soil information is available was selected (standard area grid with a resolution of 1 km × 1 km; Hokkaido Central Agricultural Experiment Station 1991). The area covers 24,551 km² and 31% of Hokkaido (78,389 km²). The annual precipitation in Hokkaido is shown in Fig. 2. The average annual precipitation for the study area is 1,120 mm. The average annual temperature for the study area is 5.8°C. These climate factors were calculated from interpolated climatic data for the standard area grid developed by National Institute for Agro-Environmental Sciences (Seino 1993).

Description of DRASTIC

DRASTIC (Aller et al. 1987) consists of seven environmental factors, which are listed below.

- Depth to water (D)
- Net recharge (R)
- Aquifer media (A)
- Soil media (S)

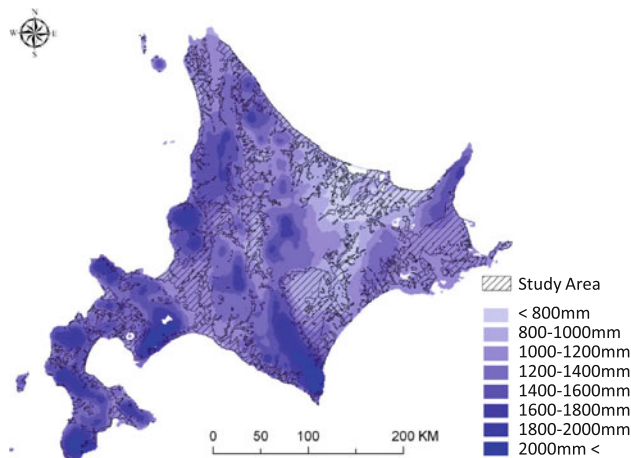


Fig. 2 Annual precipitation of Hokkaido in climatological normals from 1971 to 2000. The precipitation data were derived from interpolated climatic data on a standard area grid developed by National Institute for Agro-Environmental Sciences (Seino 1993)

- Topography (T)
- Impact of the vadose zone media (I)
- Hydraulic conductivity of the aquifer (C)

Each factor has ratings classified from corresponding parameters with weights to show the relative importance of each factor. The pollution potential is calculated as vulnerability using the following equation:

$$\text{Pollution potential} = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw \tag{1}$$

where *r* = rating and *w* = weight.

Modification to DRASTIC

Selection of factors

In this study, five factors were selected for evaluation from the seven original DRASTIC factors (Table 1): Depth to

Table 1 Selected factors and weights for modified DRASTIC method used in this study

Factors	Original DRASTIC	Modified DRASTIC in this study	Weight
Depth to water	✓	✓	5
Net recharge	✓	✓	4
Aquifer media	✓	–	3
Soil media	✓	✓	2
Topography	✓	✓	1
Impact of the vadose zone media	✓	✓	5
Hydraulic conductivity of the aquifer	✓	–	3

water (D), net recharge (R), soil media (S), topography (T), and impact of vadose zone media (I). These factors explain the vertical movement of contaminants to the aquifer. There are two reasons for selecting these factors and excluding aquifer media (A) and hydraulic conductivity of the aquifer (C). The first reason is the specific purpose of our study. Factor C together with the gradient and porosity of the aquifer, which is represented by factors T and A, beneath a site influences the rate of movement of an introduced pollutant away from the point of introduction (Aller et al. 1987). However, in our study, only arable land was selected as the study area, and aiming for appropriate fertilizer application management, the study focused on the nitrate input from this land considering the land as a non-point source of pollutants. Hence, for our goal, it is reasonable to evaluate the in situ risk of vertical movement of pollutants to the aquifer rather than their flux and dispersion risk within the aquifer. The second reason is the characteristics of the aquifer in the study area. Figure 3 shows a geomorphologic land classification map of Hokkaido. Most of the study area was classified as an alluvial plain, terrace, or pyroclastic flow plateau [19,310 km² (78.6%)]. This implies that shallow aquifers tend to consist of unconsolidated layers. The data from a columnar section show that 81.7% of the wells in the Hokkaido region have aquifers consisting of sand or gravel media ($N = 3,075$). These section data are obtained from a groundwater survey carried out by the National Land Survey Division of the Land and Water Bureau of the Ministry of Land, Infrastructure, and Transport. The survey results have been made public. Therefore, the rating for Factor A (aquifer media) should have a narrow range. As mentioned in the DRASTIC manual, the values of Factor C (hydraulic conductivity of the aquifer) may be estimated from the grain size or rock types whose classification categories are very close to those of Factor A. In the original DRASTIC

rating system, high ratings for both Factor C and Factor A are associated with high pollution potential. Therefore, the value of Factor C should be positively correlated with that of Factor A and should have a narrow range in the Hokkaido region. Therefore, the relative effect of these two factors on vulnerability evaluation was expected to be smaller in the Hokkaido region as than that in Europe or USA, where structural plains or limestone areas are widely distributed.

Therefore, in this study, the groundwater vulnerability was calculated by the formula

$$Gvhokk = DrDw + RrRw + SrSw + TrTw + IrIw \quad (2)$$

where $Gvhokk$ = groundwater vulnerability in Hokkaido, r = rating and w = weight.

Modification of net recharge rating

In the original DRASTIC rating system, the net recharge factor has a relatively narrow range, and the maximum recharge rate is 254 mm/year. The net recharge is evaluated as the water available for transporting contaminants vertically to the water table (Aller et al. 1987). Therefore, in DRASTIC, the greater the recharge, the greater the potential for groundwater pollution. DRASTIC manuals also document that the net recharge factor controls the dispersion and dilution of contaminants in the vadose zone and saturated zone (Aller et al. 1987). However, the ranges and associated ratings do not reflect dilution; hence, the rating is only true until the amount of recharge is great enough to cause dilution (Aller et al. 1987). In the study area, the average annual precipitation is 1,120 mm, and the range of recharge rate is wider than that allowed in the original DRASTIC. Miki et al. (2000) mentioned that the less surplus water there is in soil, the less permissible amount of residual nitrate in soil is to prevent nitrate leaching to groundwater. This suggests that “the water

Fig. 3 Geomorphologic land classification map of Hokkaido. Japan Engineering Geomorphologic Land Classification Map (Wakamatsu et al. 2005) was reclassified. The location data of active volcanoes were obtained from the website of Japan Meteorological Agency

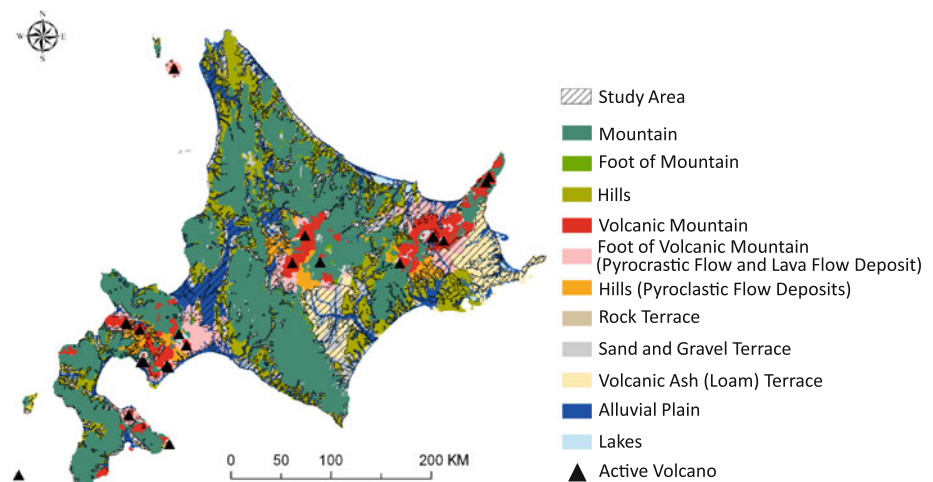


Table 2 Ranges and ratings for modified DRASTIC factors

Rating	Ranges of factors				
	Depth to water (m)	Net recharge (mm/year)	Soil media	Topography (%)	Impact of vadose zone media
10	0.00–1.52 (0–5 feet)	<95	–	0–2	–
9	1.52–4.57 (5–15 feet)	95–105	Sand	2–6	Basalt/Quaternary volcanic deposit
8	–	105–120	–	–	Sand and Gravel
7	4.57–9.14 (15–30 feet)	120–140	–	–	–
6	–	140–160	Sandy loam	–	Limestone/Sandstone
5	9.14–15.24 (30–50 feet)	160–200	Loam	6–12	–
4	–	200–260	Silty loam	–	Metamorphic/Igneous
3	15.24–22.86 (50–75 feet)	260–360	Clay loam	12–18	Silt/Clay/Shale
2	22.86–30.48 (75–100 feet)	360–600	–	–	–
1	>30.48 (>100 feet)	>600	Clay	>18	Confining layer

available for dilution of nitrate” is a more reasonable and suitable explanation for net recharge in Hokkaido rather than as a transporter. Accordingly, the recharge factor was rated as the greater the recharge, the lower the potential for groundwater pollution, which is opposite to the original DRASTIC.

Individual parameters

Depth to water

The data for the depth to water were collected from wells surveyed by the Environmental Division of Hokkaido Prefecture (Fiscal year of 1999–2007; 2,298 data points). The water table level was interpolated from the geographical locations of wells using the universal Kriging method (Huijbregts and Matheron 1971). The output resolution was set to the standard area grid (1 km × 1 km resolution) to fit the other factors. The area was rated by the original DRASTIC standard (Table 2).

Net recharge

The net recharge was defined as the difference between the annual evapotranspiration and precipitation over a standard area grid (1 km × 1 km resolution). The Makkink formula (Makkink 1957), which uses temperature and radiation as parameters, was applied to evapotranspiration calculation. All climatic data were collected from interpolated climatic data on a standard area grid developed by National Institute of Agro-Environmental Sciences (Seino 1993). As mentioned above, the greater the recharge, the lower the rating. Tabuchi and Takamura (1985) calculate nitrate concentration within the arable land soil as a simple equation given below.

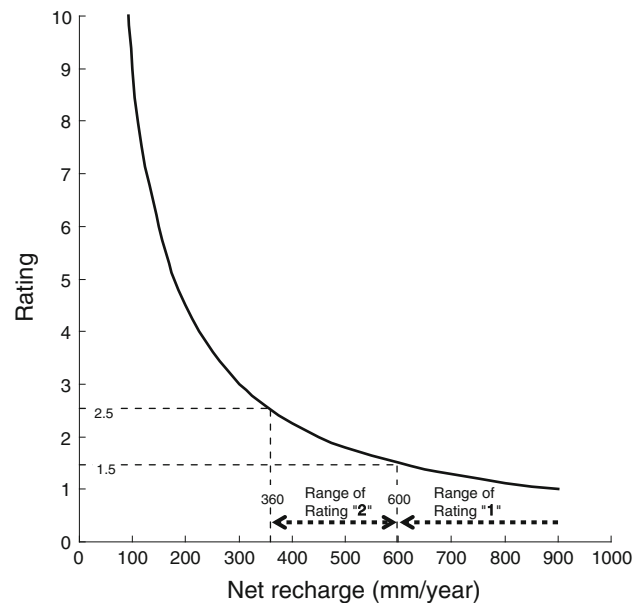


Fig. 4 Graph of ranges and ratings for net recharge

$$N_{con} = \frac{E_{rate} \times Fert}{W_{perc}} \tag{3}$$

where N_{con} = Nitrate concentration in percolation water (mg/L), E_{rate} = Elution rate, $Fert$ = Fertilizer input (kg/ha), W_{perc} = Percolation water (mm/year).

On the basis of this formula, the elution rate from soil and the fertilizer input were treated as fixed numbers; the upper 5–10% of the net recharge was set as the minimum rating of 1. In consequence, as shown by the graph in Fig. 4, areas with a calculated recharge of more than 600 mm/year were assigned the minimum rating of 1, and the maximum rating of 10 was given to locations with rates under 95 mm/year (Table 2).

Soil media

For soil media information, agricultural soil information on a standard area grid (1 km × 1 km resolution) (Hokkaido Central Agricultural Experiment Station 1991) was used. Soil texture information was extracted from this dataset and rated by the original DRASTIC standard (Table 2). In addition, this data set was stratified into four classes by the depth of soil. Therefore, the soil media rating for each grid was calculated as the mean rating weighted by the thickness of each layer.

Topography

The slope (in percentile value) was calculated from a digital elevation model (DEM) with a 50-m resolution; this was derived from the Geographical Survey Institute of Japan. The mean values within a standard area grid (1 km × 1 km resolution) were used for rating the topography factor. The original DRASTIC rating system was used for this factor (Table 2).

Impact of vadose zone

For information on the vadose zone, a dataset of the physical properties of underground soil was prepared from the soil's columnar sections at borehole points. The data were derived from a groundwater survey viewable to the public performed by the National Land Survey Division of the Land and Water Bureau in the Ministry of Land, Infrastructure, and Transport. The zone above the water table was defined as the vadose zone by overlaying the corresponding dataset with the depth to water data. Information for 0–1-m depth was excluded so as to avoid duplicating the evaluation with the soil media. Each stratum belonging to a single borehole point was evaluated by the original DRASTIC standard (Table 2). The representative rating for each borehole point was calculated as the mean rating weighted by the thickness of the strata. Spatial interpolation was carried out using the Thiessen polygon method by taking geomorphic differences into consideration. The interpolation procedure is shown as a schematic diagram in Fig. 5. First, Thiessen polygons were constructed from the geographic location of a borehole point (Step 1 in Fig. 5). Second, a geomorphic classification map on a standard area grid (1 km × 1 km resolution) (Wakamatsu et al. 2005) was overlaid with the Thiessen polygons (Step 2 in Fig. 5). Third, areas belonging to the same geomorphic category and the Thiessen polygon were extracted for the borehole point (Step 3 in Fig. 5). This spatial processing was based on the principle that different geomorphic regions must have different conditions

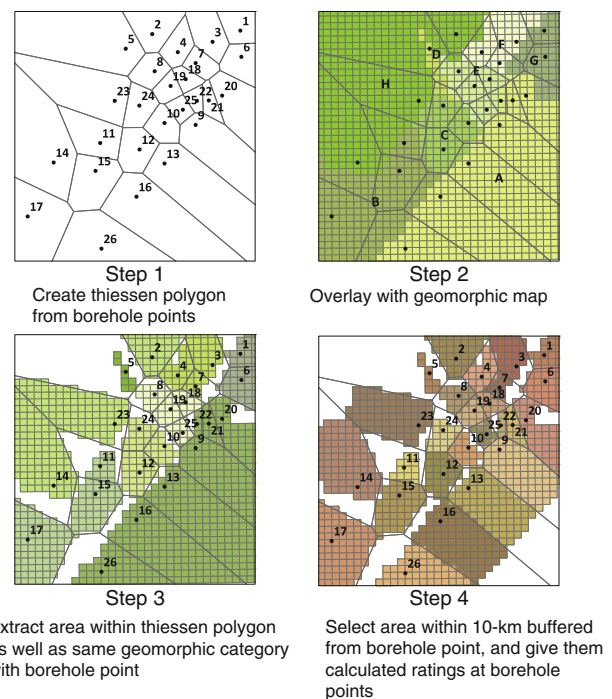


Fig. 5 Schematic diagram of spatial interpolation procedure for impact of vadose zone media

of sedimentation even if the area is segmented the same way by Thiessen polygons. Finally, areas within a 10-km buffer from the borehole point were selected (Step 4 in Fig. 5). The calculated rating for the borehole point was given to these areas.

Output of vulnerability map and validation

The study area was classified into the three land categories of upland field, paddy field (for rice), and pasture. These are based on the land category attributes in the agricultural soil information used for the soil media factor. For each land category, relationships between the vulnerability and the frequency of wells with nitrate concentrations exceeding the environmental standard (10 mg/L) were examined. A single-factor generalized liner model (GLM) with a logit-link function and quasi-binomial distribution was introduced for this examination. For the explanatory variable, vulnerability was classified into classes with 10-point intervals.

GIS and statistic analysis

To build and manage a database of columnar sections from the borehole data, Microsoft Access 2003 (Microsoft, Redmond, WA, USA) was used. Arc GIS Desktop 9.3 (ESRI, Redlands, CA, USA) was used for spatial interpolation and other analysis with GIS-based data. The

statistical analysis was performed using R ver.2.10.1 (R Development Core Team 2009).

Results

The rating map for each factor is shown in Fig. 6. The distributions of vulnerability score in the study area are shown in Fig. 7. The vulnerability evaluation was successful in 30.5% (7,494 km²) of the study area. In northern Hokkaido, the cultivated land was widely distributed, and vulnerability calculations were incomplete because of an inadequate dataset for the depth to water (D) and impact of the vadose

zone (I). Areas with a high vulnerability are closely distributed around the Sea of Okhotsk, Tokachi river watershed, and southern Ishikari lowlands. The I and R factors for these three areas had relatively high ratings. In addition, the S and T factors for the Tokachi river watershed and southern Ishikari lowlands had high ratings. Figure 8 shows scatter plots between the vulnerability categories and the percentage of wells exceeding the environmental standard for nitrate in groundwater for upland fields, paddy fields, and pastures. The frequency of wells exceeding the standard in upland fields is reasonably explained by vulnerability evaluation results (GLM: logit-link, quasi-binomial distribution, $Y = [1 + \exp(6.873765 - 0.045988 \times X)]^{-1}$, $p = 0.0006$).

Fig. 6 Maps showing ratings for five factors controlling groundwater vulnerability. The letters at the top right corner of each map indicate the following factors: *D* depth to water, *R* net recharge, *S* soil media, *T* topography, and *I* impact of vadose zone media

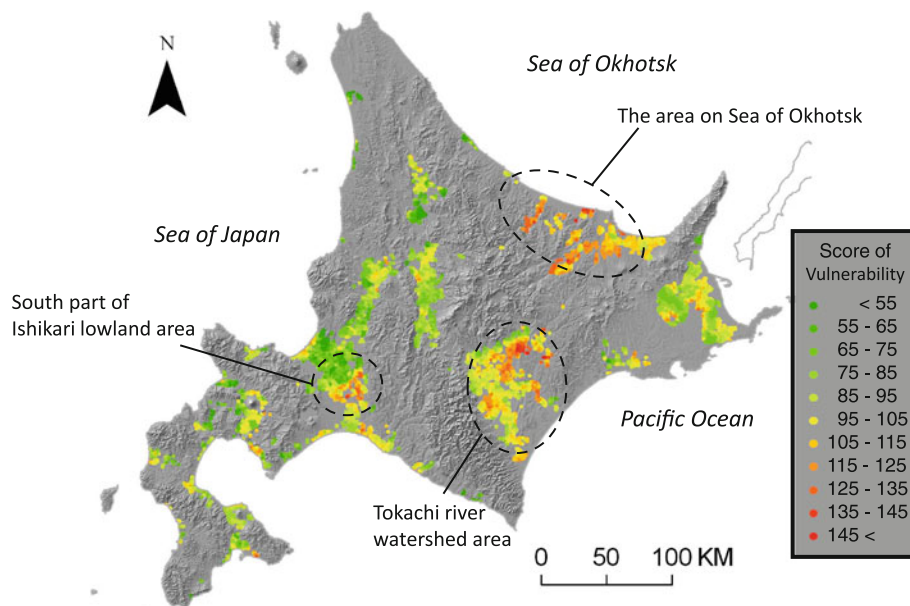
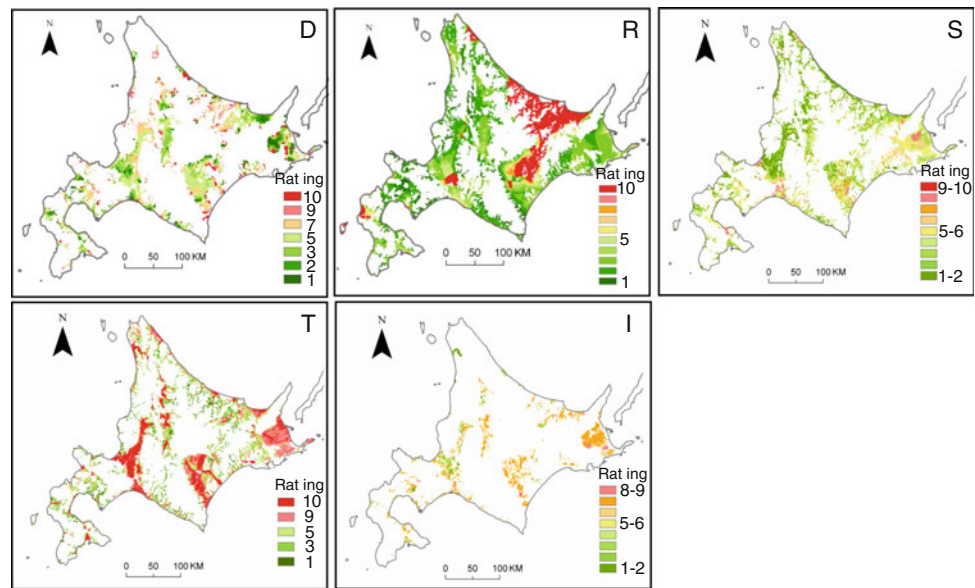


Fig. 7 Spatial distribution of groundwater vulnerability score

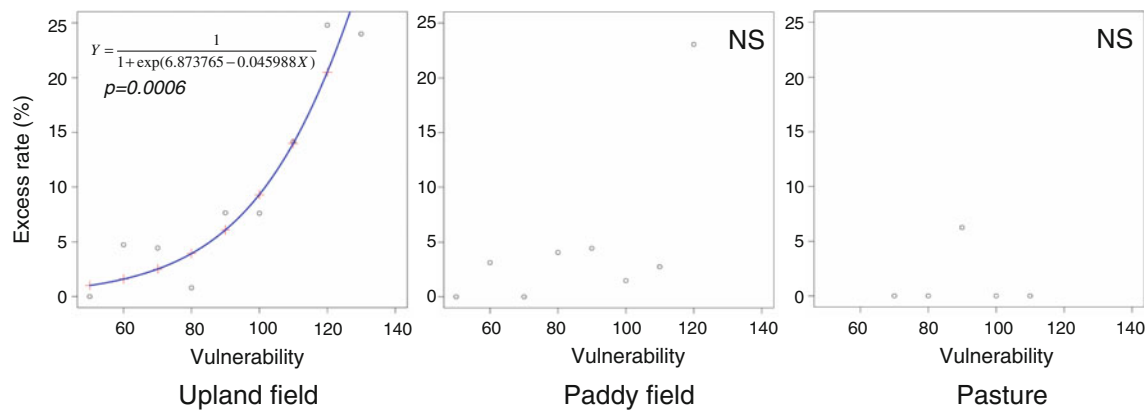


Fig. 8 Frequency of wells with NO_x-N concentrations exceeding 10 mg/L for each vulnerability category. A generalized liner model with logit-link function was used with a quasi-binomial distribution

However, those in the paddy fields and pasture cannot be clearly explained by vulnerability ($p = 0.2785$ and 0.897 , respectively).

Discussion

Vulnerability evaluation and its validation

The areas around the Sea of Okhotsk and the southern Ishikari lowlands, which have high I and S ratings, are surrounded by active volcanoes and calderas. These areas are covered by volcanic deposits such as pumice falls, pyroclastic flows, and volcanic ash. These types of deposits usually exhibit high infiltration rates because of their high porosity. This geological characteristic may affect the groundwater vulnerability through the I and S factors. Areas with high ratings for the net recharge are distributed around the Okhotsk coast and Tokachi river watershed. This is due to the relatively low precipitation in these areas as compared to others. The vulnerability evaluation results reasonably explain the frequency of wells exceeding standards only in the case of upland fields. This can be attributed to two factors: the distinctive soil structure characteristics of paddy fields and the low rate of fertilizer application in the case of pasture. The soil in paddy fields remains submerged in water, except at the later stages of the rice-growing cycle. Therefore, a plow layer with low permeability is formed within a vertical cross section of the soil (Tsuruta et al. 1997). The lower part of the plow layer is saturated with irrigation water, thereby inducing anaerobic conditions. It works as a reduction layer (Takai and Kamura 1966) where denitrification occurs. When water containing nitrate passes through this layer, the nitrate concentration decreases (Sasaki et al. 1998). Thus, the concentration of fertilizer-induced nitrate-nitrogen is reduced in groundwater regardless of vulnerability.

with p value (95% confidence interval) estimation for predicted probabilities after logistic regression

Nitrogen still accumulates in the upper part of the plow layer, although nitrate may escape from the water as nitrogen gas. In upland fields, saturated plow layers such as those found in paddy fields are rare. Therefore, denitrification is not remarkable, and leaching occurs relatively easily. Thus, the intrinsic vulnerability of soil to contamination is directly reflected by the nitrate concentration in groundwater. The difference between vulnerability classes is unclear in the case of pastures, even though plow layers are hardly found. This is because pastures require a relatively low amount of fertilizers (e.g., 4–10 kg N/10 a/year for timothy; Department of Agriculture, Hokkaido Government 2002) and have a high nitrogen output, due to harvesting, as compared to croplands (146 kg/ha/year for pastures; Matsumoto and Tou 2006).

Application to fertilizer management

Our modified DRASTIC method provides a reasonable explanation for the present state of nitrate in groundwater for upland fields. In contrast, in the cases of paddy fields and pastures, vulnerability did not exhibit a clear relationship with the frequency of wells exceeding the standard. In Hokkaido, upland fields dominate cultivation fields (35.7% of arable land), unlike other regions in Japan (Japan average excluding Hokkaido = 21.8% of arable land; Ministry of Agriculture, Forestry and Fisheries 2008). Further, under the ongoing policy for acreage allotment for rice production, the government has recommended changing crops or implementing a crop rotation system (Ministry of Agriculture, Forestry and Fisheries 2007). When paddy fields are changed to upland fields for cultivation of other crops, the saturated reduction layer disappears, inducing nitrate leaching (Ishikawa et al. 2005). In these circumstances in the Hokkaido region, our results can be mainly applicable to serve two purposes. The first purpose is fertilizer application management in upland fields

according to the evaluation of nitrate contamination risk for groundwater. The second one is decision-making for a spatial arrangement of arable land in terms of the potential risk of fertilizer-induced nitrate contamination accompanied by changing crop or crop rotation. In this study, five factors were selected for evaluation from the seven DRASTIC factors. The source data that we have used to prepare these five datasets are almost freely available with the same spatial accuracy throughout Japan. Furthermore, in other East Asian regions, with climate similar to that of Japan, these five datasets can be obtained for a wider area than the datasets for the other two factors. This is because the selected factors can be evaluated close to the earth surface. Thus, this method has potential for application to eastern Asia regions to evaluate relative vulnerability difference in fertilizer-induced groundwater contamination. The results of this study will contribute not only to strategic decision-making for fertilizer application but also to the development of a consensus among farmers, the local communities, and the government to minimize the impact of fertilizers on the local environment. Governments administering relatively large areas such as Hokkaido must develop macroscopic evaluation methods to frame an overarching agricultural policy that takes environmental protection into consideration.

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