

Evaluation of waste disposal site using the DRASTIC system in Southern Korea

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Abstract As a systematic approach to waste disposal site screening for groundwater pollution protection, the DRASTIC system developed by the US Environmental Protection Agency (USEPA), was introduced at Younggwang County in Korea. Hydrogeological spatial databases for the system include information on depth to water, net recharge, aquifer media, soil media, topographic slope, hydraulic conductivity and lineament. Using the databases, the DRASTIC system and a GIS, the regional groundwater pollution vulnerability of the study area was assessed. The fracture density extracted from lineament maps was added to the DRASTIC system to take into account the preferential migration of contaminants through fractures. From the results of the study, a degree of groundwater pollution vulnerability through the study area was easily interpreted, and waste disposal sites could be screened for groundwater protection.

Keywords DRASTIC · GIS · Waste disposal site · Groundwater vulnerability · Korea

Introduction

Because hazardous polluting material can be spread widely by groundwater near a landfill site, groundwater pollution protection is a very important factor in waste disposal site location. Therefore, groundwater pollution vulnerability should be assessed. The groundwater pollution vulnerability means the relative possibility of groundwater pollution

under either point or non-point pollutant application. This term is based on the characteristics of the hydrogeological setting and does not take into consideration any of the existing pollution sources. Potential contamination of groundwater at any given location depends upon several physical and environmental factors. The waste site, especially for hazardous and solid waste disposal, must be in an area with a low vulnerability to groundwater pollution, to prevent easy movement by the groundwater. Thus, the objective of this study is to screen for waste disposal siting with respect to groundwater protection by performing a groundwater vulnerability assessment using a modified DRASTIC (Aller and others 1987) approach combined with a Geographic Information System (GIS). The hydrogeological factors that affect the potential for groundwater pollution, defined in the DRASTIC system are as follows; D=depth to water, R=net recharge, A=aquifer media, S=soil media, T=topography or slope, I=impact of vadose zone media, and C=hydraulic conductivity.

A primary objective of the site selection process is to ensure that new facilities are located at intrinsically superior sites that, by virtue of their natural features and land-use setting, provide a high degree of protection to public health and the environment. A site selection process usually proceeds through a phased approach, as depicted in Fig. 1. It begins with the use of regional screening techniques to reduce a large study area. Because of this screening, the search areas will have higher probabilities of containing suitable sites. The next phase evaluates the discrete search areas in more detail and identifies candidate sites within them. These candidate sites are then evaluated in even more detail at a site-specific level of analysis to provide the basis for selecting a site for the facility. Most site screening methods require siting criteria and factors. A siting factor is associated with a specific consideration important in judging the suitability of a site. A criterion is a definitive threshold of acceptability for a siting factor. A great number of siting factors can be applied when selecting the site for a hazardous waste facility. Table 1 lists some example factors frequently used in such endeavors (LaGrega and others 1994). This study is a regional screening process in the waste disposal site selection process by only considering the groundwater pollution problem. Also, the DRASTIC system is a relative evaluation model at the regional scale, not a site-specific assessment model. Thus, in this study, the screening for the waste disposal site was performed using the DRASTIC

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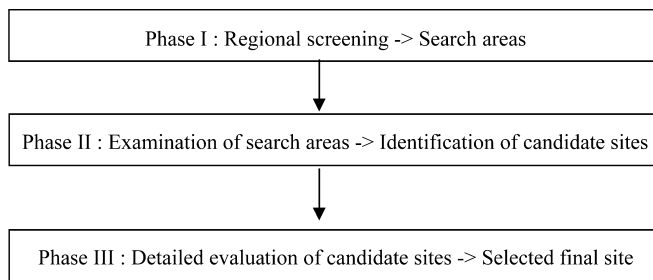


Fig. 1
Phased site selection process

system in a Arc/Info GIS environment. In the waste disposal siting, other factors such as surface water, environmentally sensitive lands and population are very important but are not considered in this study. In this study, the procedure for implementing the DRASTIC method and screening for waste disposal siting using GIS involves: (1) collecting hydrogeological and geological data, (2) standardizing and digitizing source data, (3) constructing an environmental database, (4) analyzing the DRASTIC factors, (5) calculating the DRASTIC index for the hydrogeological settings, (6) rating these areas as to their vulnerability to contamination, and (7) screening for waste disposal siting.

There have been many studies on DRASTIC system application using GIS (Smith and others 1994; Merchant 1994; Melloul and Collin 1998; Secunda and others 1998; Kim and Hamm 1999; Fritch and others 2000a, 2000b; Cameron and Peloso 2001; Mclay and others 2001; Al-Zabet 2002; Davis and others 2002). Also, the DRASTIC system is widely used in Korea (Lee and Kim 1996; Min and others 1996; Lee and Choi 1997; Jo and others 1999; Lee and others 1998).

Groundwater pollution vulnerability assessment system: modified DRASTIC system

There are many groundwater pollution vulnerability assessment systems. From among these, the DRASTIC system was used in this study and developed by USEPA in 1987 to assess relative groundwater pollution vulnerability using hydrogeological factors. The system can be used as a preliminary screening tool in the selection of well sites and waste disposal sites, and as a basic tool in land-use plan-

ning for groundwater protection. In addition, it can be used for monitoring purposes and for efficient allocation of resources for remediation. The system is not for local analysis but for regional analysis and is developed with the assumption that a pollutant has mobility in water introduced at the surface and is carried towards the groundwater by infiltration.

In addition to the seven DRASTIC factors, adsorption, travel time, and dilution are also major factors in groundwater vulnerability assessment (Rosen 1994). The DRASTIC model assumes that: (1) any contaminant is introduced at the land surface; (2) the contaminant is introduced into the groundwater by rainfall; (3) the contaminant has the mobility of the water; and (4) the area evaluated is 0.4 km² or larger.

The DRASTIC system is composed of two major parts: (1) the designation of mappable units, termed hydrogeological setting; and (2) the application of a numerical scheme of relative ranking of hydrogeological factors, which helps to evaluate the relative groundwater pollution potential of any hydrogeological setting. Hydrogeological setting is a composite description of all the geological and hydrological factors controlling groundwater flow into, through, and out of an area (Kim and Hamm 1999). The hydrogeological factors of the study area were obtained from the hydrogeological maps of Younggang-Gun Province (Choi and others 1997).

Each DRASTIC factor has been evaluated with respect to the others to determine their relative importance so that a relative weight ranging from one to five could be assigned to each factor (Table 2). Each factor was further divided into either ranges or significant media types and a rating representing the relative significance of pollution vulnerability was assigned to each range (Table 2). The DRASTIC system allows the user to determine a numerical value that shows areas more likely to be susceptible to groundwater contamination relative to others. The higher the DRASTIC index, the greater the groundwater pollution vulnerability. There are two types of DRASTIC systems. One is a general DRASTIC system and the other is a pesticide DRASTIC system. The pesticide DRASTIC system is designed to be used where the activity of concern is the application of pesticides to an area and differs in the assignment of weights. The equation for determining the DRASTIC index is:

$$\text{DRASTIC Index (Pollution vulnerability)} = DrDw + RrRw + ArA + SrSw + TrTw + IrIw + CrCw \quad (1)$$

Table 1
Example hazardous waste facility siting factors (LaGrega and others 1994)

Category	Example siting factors
Surface water	Flood hazard areas, drinking water supplies, reservoirs
Groundwater	Hydraulic conductivity, depth to groundwater, thickness of clay deposits, aquicludes/aquitards, recharge areas, proximity to wells, karst area, groundwater flow direction
Environmentally sensitive lands	Wetlands, habitat for endangered species, parks
Population	Proximity to dwelling units, proximity to schools, population density

Table 2
Assigned weights for DRASTIC features

Factors	Weight		Range(cm)	Rating	Typical rating			
	General	Agricultural						
Depth to water (cm)	5	5	0–152.4	10				
			152.4–457.2	9				
			457.2–914.4	7				
			914.4–1,524.0	5				
			1,524.0–2,286.0	3				
			2,286.0–3,048.0	2				
			3,048.0+	1				
Net recharge (cm)	4	4	0–50.8	1				
			50.8–101.6	3				
			101.6–177.8	6				
			177.8–254.0	8				
			254.0+	9				
Aquifer media	3	3	Massive shale	1–3	2			
			Metamorphic/igneous	2–5	3			
			Weathered metamorphic/igneous	3–5	4			
			Glacial till	4–6	5			
			Bedded sandstone, limestone, shale	5–9	6			
			sequences					
			Massive sandstone	4–9	6			
			Massive limestone	4–9	6			
			Sand and gravel	4–9	8			
			Basalt	2–10	9			
			Karst limestone	9–10	10			
			Thin or absent	10				
			Gravel	10				
Soil media	2	5	Sand	9				
			Peat	8				
			Shrinking and/or aggregated clay	7				
			Sandy loam	6				
			Loam	5				
			Silty loam	4				
			Clay loam	3				
			Muck	2				
			Nonshrinking and nonaggregated clay					
			Topography (%)	1	3	0–2	10	
						2–6	9	
						6–12	5	
						12–18	3	
18+	1							
Impact of the vadose zone media	5	4	Confining layer	1	1			
			Silt/clay	2–6	3			
			Shale	2–5	3			
			Limestone	2–7	6			
			Sandstone	4–8	6			
			Bedded limestone, sandstone, shale	4–8	6			
			Sand and gravel with significant silt and clay	4–8	6			
			Metamorphic/igneous	2–8	4			
			Sand and gravel	6–9	8			
Basalt	2–10	9						
Hydraulic conductivity (GPD/Ft ²)	3	2	Karst limestone	8–10	10			
			1–100		1			
			100–300		2			
			300–700		4			
			700–1,000		6			
			1,000–2,000		8			
2,000+		10						

where r=rating, w=weight, D=depth to water, R=net recharge, A=aquifer media, S=soil media, T=topography, I=impact of vadose zone media, and C=hydraulic conductivity.

Once the DRASTIC index has been computed, it is possible to identify areas that are susceptible to groundwater pollution. A modified DRASTIC system is developed in this study. The system combines the DRASTIC system and

the lineament density. Lineament refers to numerous linear features of the land surface. However, in this study, it only represents geological structures such as fractures and joints. Lineament is closely related to groundwater flow and contaminant migration resources; therefore, higher lineament density values may mean more potential groundwater contamination. Particularly in Korea, most of the aquifers are developed in fractured rock as groundwater mainly moves through faults and fractures. The lineament density is similar to the aquifer media, but the aquifer media only take into consideration lithology, not fault and fracture. Therefore, by applying an analysis of lineament density to the DRASTIC system, groundwater pollution vulnerability can be assessed more accurately. Using the lineament database, lineament density is obtained from the photolineament value (Hardcastle 1995). The procedure for calculating the photolineament value is shown in Fig. 2. When considering lineament frequency, the obtained lineament density was rated in ten equal areas (about 10%). Then, the chosen range and rating was assigned to lineament density and overlaid with the DRASTIC system. The weighting of the lineament density was set to five, i.e., the highest of the DRASTIC system weighting values, because of the importance of the lineament density. The modified DRASTIC system index was thus calculated using Eq. (2).

$$\text{Modified DRASTIC index} = \text{DRASTIC index} + LrLw \quad (2)$$

where r =rating, w =weight, L =lineament density.

Study area and spatial database

The study area is Younggwang County in Korea (Fig. 3). The site lies between latitudes $35^{\circ}10'N$ and $35^{\circ}27'N$, and longitudes $126^{\circ}20'E$ and $126^{\circ}40'E$, and covers an area of 460 km^2 (Fig. 3). The geology of the study area consists of Precambrian gneiss, metasedimentary rock of an unknown age, Jurassic granite, Cretaceous volcanic rock, dikes and Quaternary alluvium. The study area has a population of 0.5 million. Efficient development and management of groundwater are needed in the study area because of the increasing demand for groundwater and the existence of various potential sources of groundwater pollution, including agricultural activities, industrialization, and seawater intrusion. Also, waste disposal siting is needed because of increasing amounts of hazardous solid waste. Topographic, geological and groundwater related data were collected through the study area. The data were formed into a spatial database using GIS, for groundwater pollution vulnerability assessment. The database construction status is shown in Table 3.

The topographic database was constructed using a 1:50,000 scale topographic map (contour interval of 20 m). This database has line attributes (vectors). The vector coverage was interpolated into a digital elevation model (DEM) with 30 m resolution, then a height distribution map, slope map, aspect map, hill-shaded map, surface water flow map

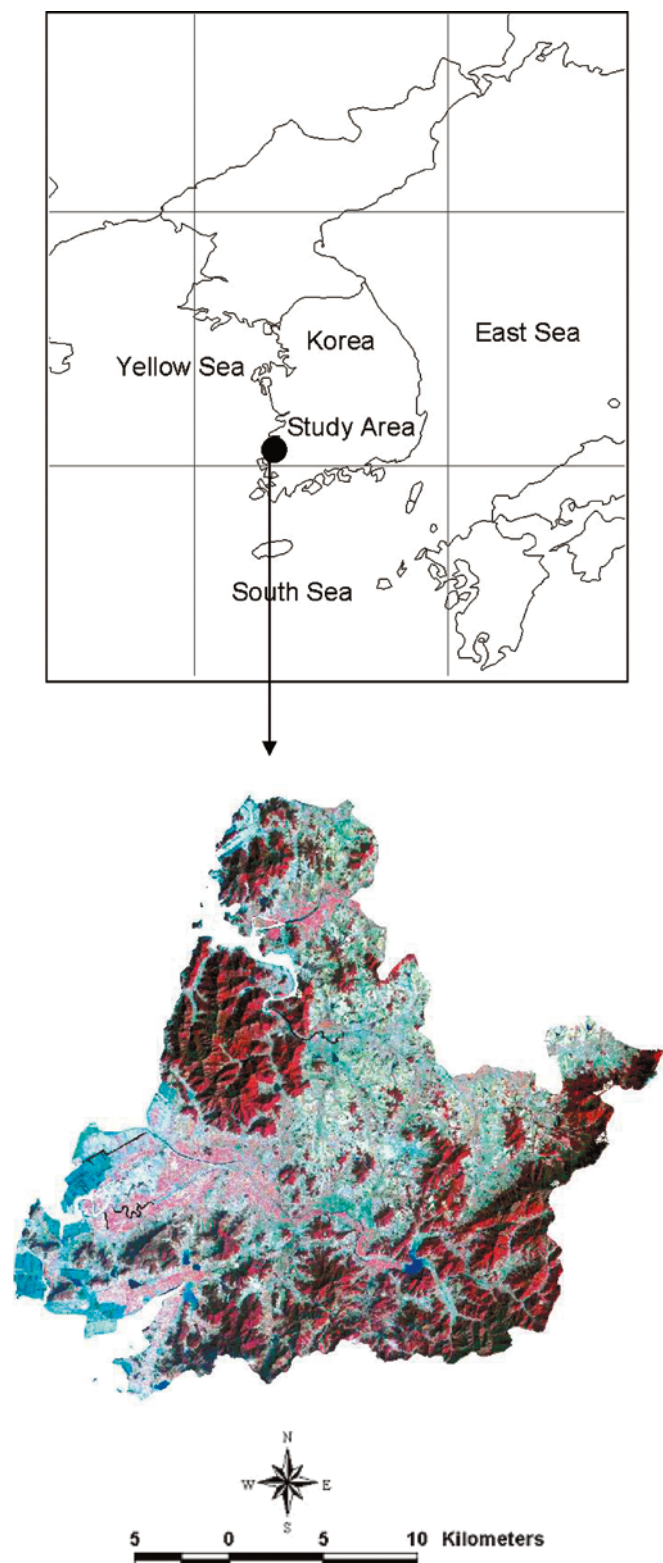


Fig. 2
Procedure to calculate the lineament density

and basin map were made using the DEM. These are needed to detect overall topography and surface water flow. A drainage database was constructed using the 1:50,000 scale topographic map. The drainage database has line and point attributes. The line attributes represent

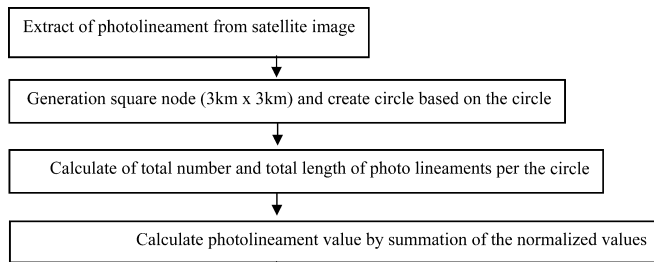


Fig. 3
Study area

Table 3
GIS layers in Youngkwang County

No.	Layer	Source data and scale
1	Contour	Topographic map(1/50,000)
2	Geology	Topographic map (1/50,000)
3	Lineament	Aerial-photo, geological map (1/50,000)
4	Soil	Soil map (1/50,000,1/25,000)
5	Water	Topographic map (1/50,000)
6	Road	Topographic map (1/50,000)
7	Administration	Topographic map (1/50,000)
8	Well data	Well inventory
9	Land use	Landsat TM Image

rivers and streams and the polygon attributes represent reservoirs, lakes and large rivers. The well database includes information about wells and groundwater. A well inventory was made six times for 252 well sites. The data from the inventory are well location, owner, address, phone number, installation year, use, depth, diameter, static water table, survey date, depth to water level, temperature, pH, EC and TDS; and they were formed to spatial database using GIS. The well database has point attributes. The geological database was constructed using a 1:50,000 scale geological map. The geological database has polygon attributes and includes lithology and fault data. The soil database was constructed using a 1:25,000 scale detailed soil map. The soil database has polygon attributes and includes soil texture, material. The land-use database has polygon attributes. It was constructed by converting the results of image processing of LANDSAT TM imagery (acquired on 17 March 1995) and was used for water budget analysis. The lineament database has line attributes. It was obtained from aerial photo interpretation and used for calculating lineament density.

Hydrogeological factors

Using the spatial database, hydrogeological factors were extracted and used for application of the DRASTIC system. Each factor of the DRASTIC system was summarized using the DRASTIC system report (Aller and others 1987) and the extraction method, which used the spatial database, is described as follows and includes the new factor: lineament density.

Depth to water

Depth to water is important as it determines the depth of the material through which a contaminant travels before reaching the aquifer. The depth to water is defined as the distance from the ground surface to the water table.

The depth to water is also important because it provides the maximum opportunity for oxidation by atmospheric oxygen. In general, there is a greater chance for attenuation to occur as the depth to water increases because deeper water levels imply longer travel times. The water level map was obtained from a report, "Hydrogeological Maps of Younggang-Gun Province" (Choi and others 1997). The water level map was made by interpolating well information from each well database. Then, depth to water level was obtained by subtracting the ground surface elevation from the water level. The ground surface elevation data were obtained from the DEM. The depth to water was obtained and range and rating distribution of depth to water are shown Fig. 4a and Table 4.

Net recharge

Net recharge is the total quantity of water (in inches), which infiltrates from the ground surface to the aquifer on an annual basis. This recharge water is thus available to transport a contaminant vertically to the water table and horizontally within the aquifer. The net recharge is the difference between total precipitation and the cumulative loss by direct runoff and effective evapotranspiration. Net recharge ratings were determined using the Soil Conservation Service (SCS) method and hydrologic data (evapotranspiration and runoff). The method adopted in this study is that of the SCS (Morel-Seytoux and Verdin 1981). This is a simple procedure, called the curve number (CN) technique which has been applied in a variety of situations since its introduction in 1954 over different watershed types, land uses, topographies and geologies. Its conceptual basis stems from the assumption that the ratio of runoff, Q , to the effective rainfall, Pe , equals the ratio of water actually retained during a runoff event to the potential maximum retention, S , realized as rainfall grows unbounded. That is,

$$\frac{Q}{Pe} = \frac{Pe - Q}{S} \quad (3)$$

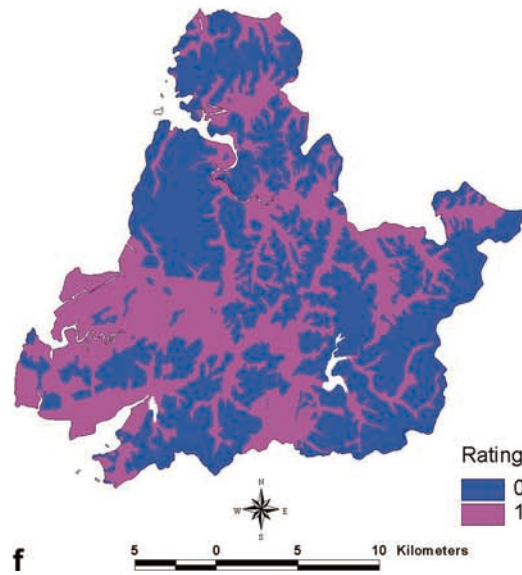
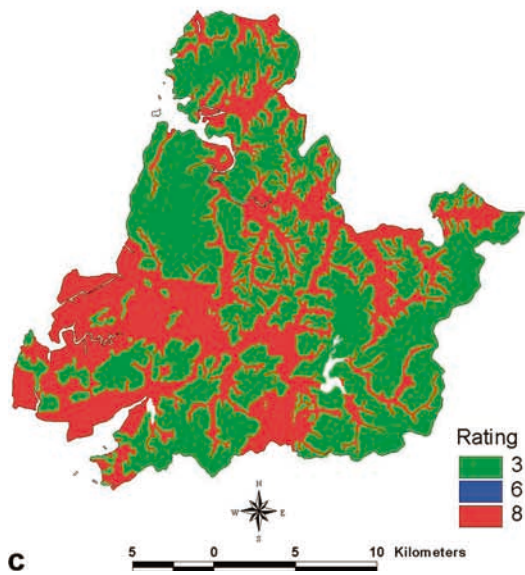
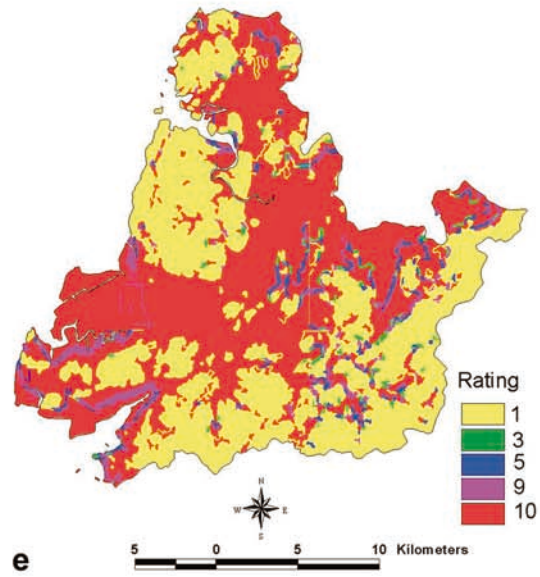
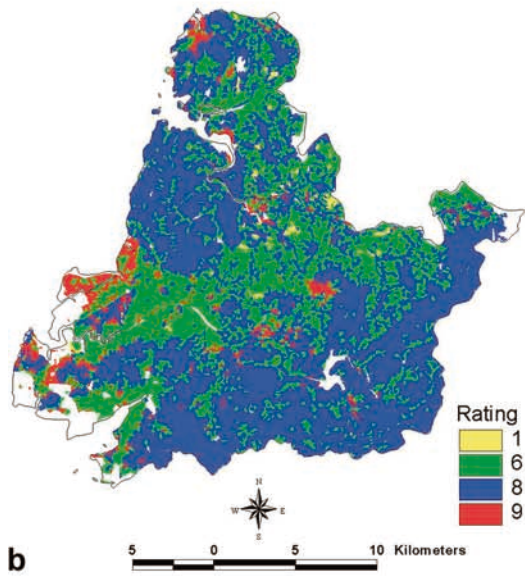
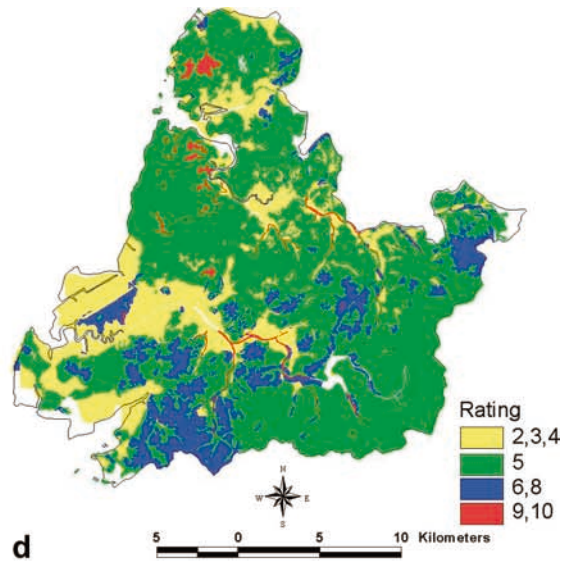
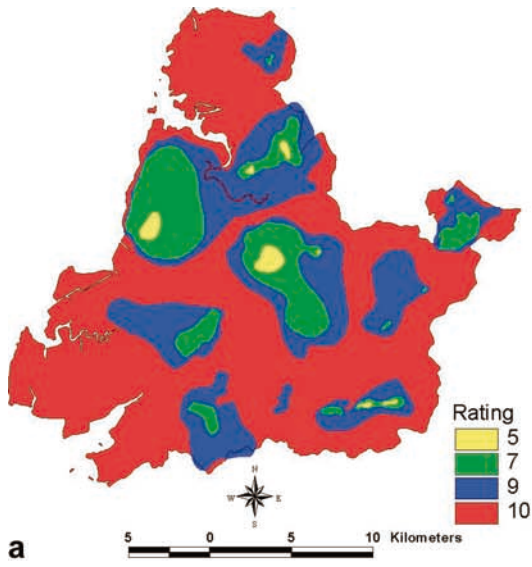
The effective rainfall, Pe , is the total runoff after runoff starts, taking account of losses from interception, and infiltration and initial surface storage. However, all these losses are grouped under an initial abstraction, Ia , which is set equal to $0.2S$ in current practice; this choice of Ia , is discussed in the next section. Thus,

$$Pe = P - Ia = P - 0.2S \quad (4)$$

where P is the total rainfall. From Eqs. (3) and (4):

$$Q = \frac{(P - Ia)^2}{(P - Ia + S)} = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (5)$$

The parameter S varies in the range $0 \leq S \leq \infty$ and can be considered as a watershed storage factor, with its lower limit representing a conceptually impervious watershed.



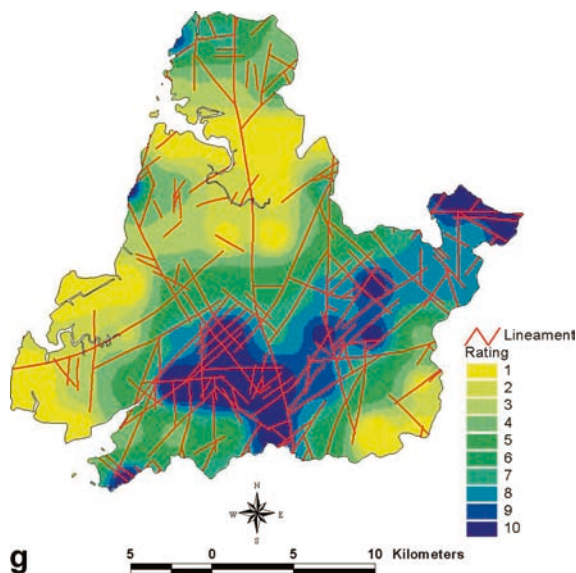


Fig. 4

Input factors for DRASTIC system. **a** Depth to water (D), **b** net recharge (R), **c** aquifer media (A), **d** soil medium (S), **e** topography (T), **f** hydraulic conductivity (C), **g** lineament and lineament density

For convenience, S , measured in mm, is mapped as follows into a dimensionless parameter, CN , where $0 \leq CN \leq 100$; correspondingly:

$$S = 25.4 \left(\frac{1000}{CN} - 10 \right) \quad (6)$$

The CN is usually estimated from handbook tables that list land use, hydrological soil group and the antecedent

moisture condition (Kottegoda and others 2000). The first step in determining the CN is to identify hydrological soil types. The detailed soil map of the study area was classified into four categories of runoff potential according to the SCS classification: low (soil type A), moderately low (soil type B), moderately high (soil type C), and high (soil type D) runoff potential. The land-use areas were classified into five categories: forest, rice field, field, residential and water. The SCS evaluation method also defines three levels of runoff potential based on the antecedent moisture conditions (AMC). The AMC is a function of five-day antecedent rainfall depth and is affected by storms that occur in the dormant and growing seasons. The AMC-I classification has a low runoff potential, AMC-II has average potential, and AMC-III has high runoff potential. Using a combination of soil and land use, the CN values were determined, and using the CN for AMC-I, AMC-II, and AMC-III, the S (maximum watershed storage) values were calculated. The cumulative rainfall (P) of 1,091.8 mm for 1996 and the cumulative direct runoff (Q) of the study area in 1996 was obtained from Eq. (5). Evapotranspiration was estimated from land use (Shin and others 1995). Therefore, net recharge was calculated as precipitation minus runoff and evapotranspiration. The result of the spatial hydrologic analysis using GIS is shown in Table 5, and the range and rating distribution of net recharge are shown in Fig. 4b and Table 6.

Aquifer media

Aquifer media refers to consolidated or unconsolidated rock, which serves as an aquifer. An aquifer is defined as a subsurface rock unit that will yield sufficient quantities of water for use. The flow system within the aquifer is

Table 4

Range and rating of depth to water

Range (m)	Rating	Area (km ²)	Area (%)
Less than 1.5	10	275,120,290	59.6
1.5–4.5	9	122,808,138	26.6
4.5–9.1	7	58,526,691	12.7
More than 9.1	5	4,791,592	1.0

Table 6

Range and rating of net recharge

Range (mm)	Rating	Area (km ²)	Area (%)
0–50.8	1	28,412,822	6.6
101.6–177.8	6	143,854,477	33.4
177.8–254.0	8	257,515,969	59.8
More than 254.0	9	935,327	0.2

Table 5

Runoff, evapotranspiration and infiltration for land use and soil type

Land use	Soil type	Precipitation (mm)	Runoff (mm)	Evapotranspiration (mm)	Infiltration (mm)
Vegetation	A	1,091.8	0	626.8	465.0
	B	1,091.8	3.90	626.8	461.1
	C	1,091.8	37.50	626.8	427.5
	D	1,091.8	81.23	626.8	393.8
Rice field	A	1,091.8	47.54	667.0	377.3
	B	1,091.8	122.50	667.0	302.3
	C	1,091.8	236.05	667.0	188.7
	D	1,091.8	318.73	667.0	106.1
Field	A	1,091.8	15.55	667.0	409.2
	B	1,091.8	42.97	667.0	381.8
	C	1,091.8	90.38	667.0	334.4
	D	1,091.8	123.34	667.0	301.54
Residential area	A	1,091.8	69.18	230.4	792.2
	B	1,091.8	181.17	230.4	680.2
	C	1,091.8	281.18	230.4	580.2
	D	1,091.8	337.70	230.4	523.7

Table 7

Range and rating of aquifer media

Type	Rating	Area (km ²)	Area (%)
Metamorphic/igneous	3	274,405,511	60.3
Bedded sandstone, limestone and shale sequences	6	8,783	0.0
Alluvium	8	180,815,344	39.7

Table 8

Range and rating of soil media

Range	Rating	Area (km ²)	Area (%)
Rock	10	4,229,672	0.9
Sand	9	3,505,262	0.8
Loamy fine sand	8	4,616,228	1.0
Clay loam	6	53,857,937	12.0
Loam	5	293,523,448	65.3
Silty loam	4	82,492,712	18.4
Clay loam	3	805,102	0.2
Silty clay loam	2	6,470,504	1.4

affected by the aquifer medium. The route and path length that a contaminant must follow are governed by the flow system within the aquifer, which is affected by the aquifer medium. Using the geological database, the information on aquifer media was obtained, and the range and rating distribution of aquifer media are shown in Fig. 4c and Table 7.

Soil media

Soil has a significant impact on the amount of recharge that can infiltrate into the ground, and hence on the ability of a contaminant to move vertically into the vadose zone. The presence of fine-textured materials such as silts and clays can decrease relative soil permeabilities and restrict contaminant migration. In the study, based on a detailed soil map of study area, the soil materials of the study area were classified according to particular criteria. Subsequently, using the soil database, soil media data were obtained, and the range and rating distribution of soil media are shown in Fig. 4d and Table 8.

Topography

Topography refers to the slope variability of the land surface. The slope will determine the extent of runoff of the pollutant and the degree of settling sufficient for infiltration. The DEM, based on a map of scale 1:50,000, was used to extract the slope, and the range and rating distribution of topography are shown in Fig. 4e and Table 9.

Impact of the vadose zone

The vadose zone is defined as the zone above the water table that is unsaturated or discontinuously saturated. The type of vadose zone media determines the attenuation characteristics of the material below the typical soil horizon and above the water table. Biodegradation, neutralization, mechanical filtration, chemical reaction, volatilization and dispersion are all processes that may occur within the vadose zone. However, in this study, because there was little data on the

Table 9

Range and rating of topography

Range (%)	Rating	Area (km ²)	Area (%)
0–2	10	2,049,288,828	44.8
2–6	9	36,901,875	8.1
6–12	5	32,239,786	7.0
12–18	3	30,389,969	6.6
More than 18	1	153,032,603	33.5

Table 10

Range and rating of hydraulic conductivity

Range	Rating	Area (km ²)	Area (%)
Alluvium	1	180,815,344	39.7
Rest of area	0	274,414,294	60.3

Table 11

Ranges and ratings of lineament density

Range of distribution density	Rating	Area (km ²)	Area (%)
0.2–1.1	1	37,306,730	12.0
1.2–1.3	2	33,196,632	9.0
1.4–1.5	3	41,487,736	10.0
1.6–1.8	4	54,609,883	12.3
1.9–2.0	5	41,026,266	9.1
2.1–2.2	6	40,229,426	9.8
2.3–2.4	7	40,522,926	8.6
2.5–2.6	8	44,340,382	11.9
2.7–2.8	9	45,540,979	7.5
2.9–4.0	10	55,692,316	9.8

vadose zone, this factor could not be considered for calculating the DRASTIC index.

Hydraulic conductivity

Hydraulic conductivity refers to the ability of the aquifer materials to transmit water, which in turn controls the rate at which ground water will flow under a given hydraulic gradient. The hydraulic conductivity is important because it controls the rate of groundwater movement in the saturated zone, thereby controlling the degree and fate of the contaminants. In this study, hydraulic conductivity data are not sufficient for mapping. Thus, using the geological database, hydraulic conductivity, which depends largely on the rock type and degree of weathering, was estimated according to Freeze and Cherry (1979). The range and rating distribution of hydraulic conductivity are shown in Fig. 4f and Table 10.

Lineament density

Water is contained in aquifers within the pore spaces of granular and clastic rock and in the fractures and solution openings of non-clastic and non-granular rock. The route that a contaminant will take can be strongly influenced by fracturing or by an interconnected series of solution

openings that may provide pathways for easier flow. In general, the more fractures or openings within the aquifer, the higher the permeability and the lower the attenuation capacity of the aquifer media. Using the lineament database, the lineament density value was obtained by using a photolineament factor (Hardcastle 1995). The range and rating distribution of lineament density value with lineament are shown in Fig. 4g and Table 11.

Assessment of groundwater pollution vulnerability and screening of waste disposal site

General pesticide and modified DRASTIC maps were produced (Figs 5, 6, 7). The modified DRASTIC map was made by overlaying the general DRASTIC map and the lineament density map. Using this DRASTIC methodology to perform the aquifer vulnerability assessment of the study area resulted in a pollution potential map of the study area. The steps for producing the maps, shown in Fig. 8, were: (1) data collection on the study area, (2) database construction using the collected data, (3) extraction of hydrogeological factors from the database, and (4) overlay analysis of the factors. The impact of the vadose zone is excluded because of insufficient data. The resultant values from Eq. (1) are as follows: the minimum DRASTIC index is 55 and the maximum DRASTIC index is 141; the minimum pesticide DRASTIC index is 66 and the maximum pesticide DRASTIC index is 187; and the minimum modified DRASTIC index is 68 and the maximum modified DRASTIC index is 191.

The final DRASTIC values have been grouped together into very low, low, moderate, high, and very high pollution potential classes. These classes represent the relative pollution potential within the study area. In terms of index extent, 55–97 is classified as indicating a very low pollution potential, 98–102 is classified as indicating a low pollution potential, 103–110 is classified as having a moderate pollution potential, 111–120 is classified as having a high pollution potential, and 121–141 is classified as indicating

a very high pollution potential. The criterion of classification is the distribution of the index value with equal area (about 20% for each range). The pesticide DRASTIC map is similar to the general DRASTIC map except for the range of the indexes, 66–118, 119–124, 125–140, 141–150 and 151–187 for very low, low, moderate, high and very high. However, the modified DRASTIC map is different to the general and pesticide DRASTIC maps. The south-middle part of the study area has very high values with the index value above 152 because of lineament density. The modified DRASTIC index is divided into five ranges: 68–114, 115–129, 130–139, 140–151 and 151–191, representing very low, low, moderate, high and very high values, respectively.

With respect to site screening for waste disposal sites, the proposed selected site is shown in Fig. 9. The site was selected by the criterion that the modified index value is very low, 68–114. Roughly, in Fig. 9, compared with satellite image of study area (Fig. 1), the middle and upper-middle sections of the study area are suitable for waste disposal sites because they have a low level and slope. However, the middle-left area and lower-right sections of the study area are mountainous areas and have a high slope.

Conclusion and discussion

Because of the increase in pollutants, degradation of the quality and quantity of the groundwater is becoming one of the major environmental problems in South Korea. Hence, it is very important to determine the degree of vulnerability to pollution based on hydrogeological factors. Therefore, the primary goal of this study was to perform an aquifer vulnerability assessment of the study area using a modified DRASTIC approach and Arc/Info GIS. Regional groundwater pollution vulnerability was analyzed accurately, quickly and easily using the DRASTIC system and GIS. To apply the DRASTIC system, topography, drainage, well, geology, soil, land use and lineament databases were designed and constructed. Using the database, hydrogeological factors such as depth to water, net recharge, aquifer media, soil media, slope, hydraulic

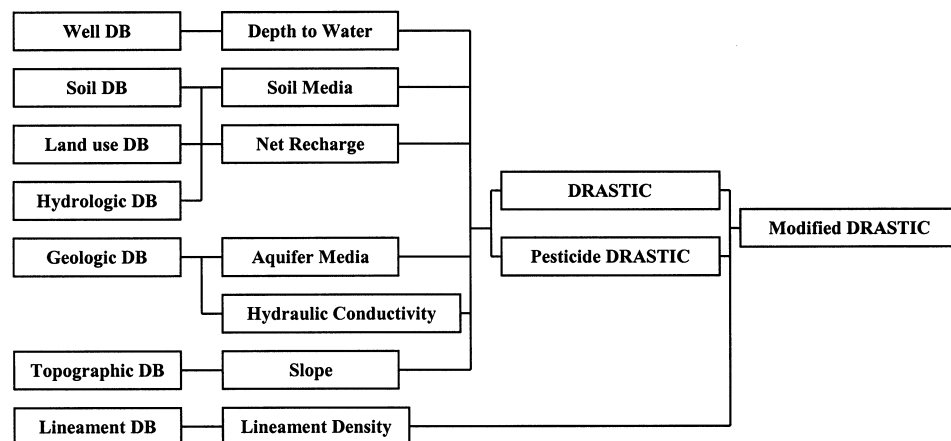


Fig. 5
DRASTIC map

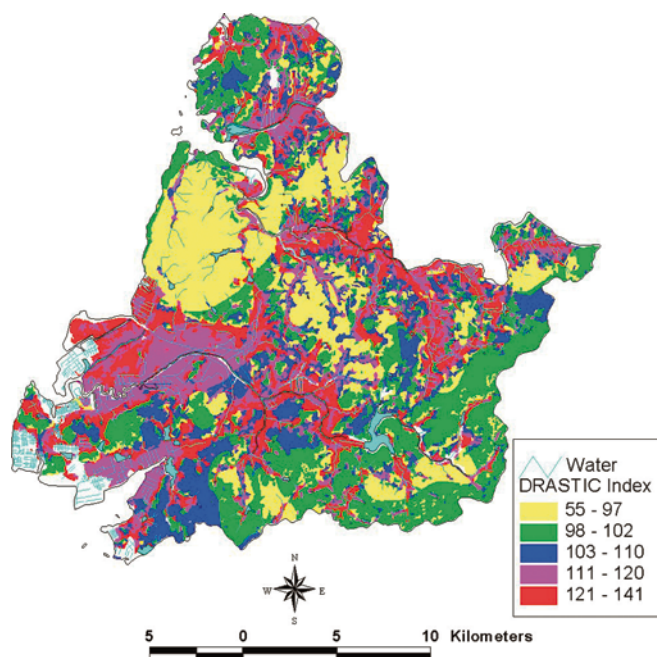


Fig. 6
Pesticide DRASTIC map

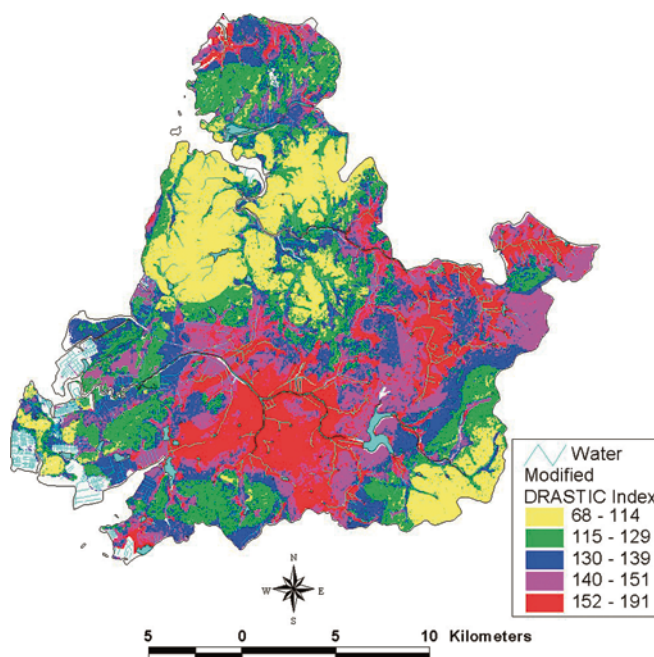


Fig. 8
Data integration for groundwater vulnerability map

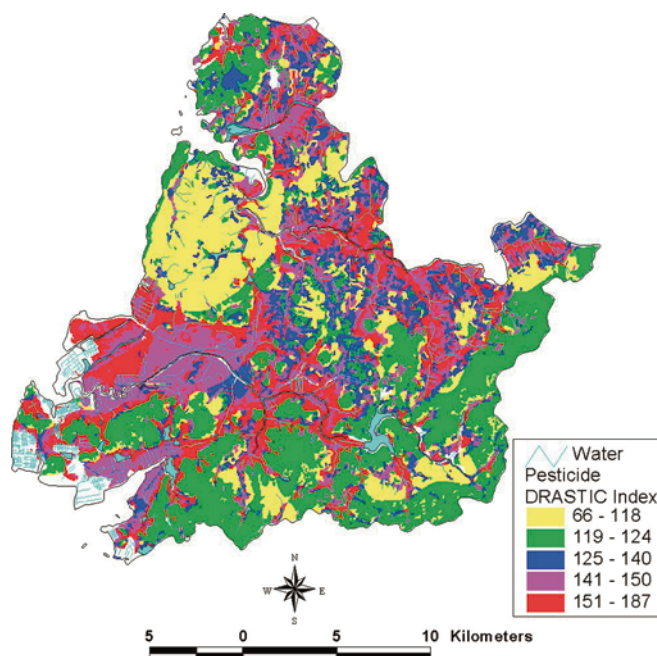


Fig. 7
Modified DRASTIC map

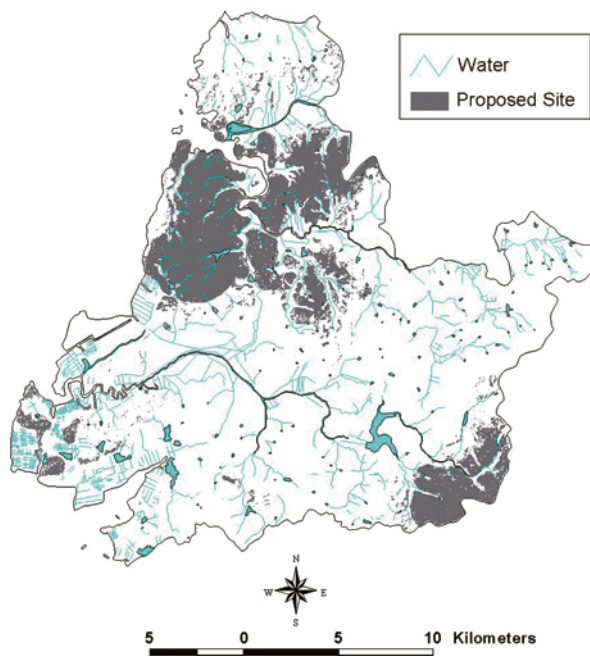


Fig. 9
Proposed site for waste disposal

conductivity and lineament density were extracted. Then, DRASTIC and pesticide DRASTIC systems were applied to the Younggwang County in Korea. The modified DRASTIC system was developed and applied to consider groundwater flow and contaminant transport through fractures. The modified DRASTIC system is a combination of the DRASTIC system and the lineament density designed for fractured aquifers. The modified DRASTIC system was

used to screen the proper waste disposal location with respect to protection of groundwater resources. These results suggest that this method of evaluating regional aquifer pollution potential more accurately assesses the pollution potential of a region and can generate information that is readily usable by agencies that are involved in groundwater protection and evaluation at a level of detail that has not been achieved before.

The groundwater pollution vulnerability map is ideal for use in future land-use planning studies, where potential contamination may occur. To aid in avoiding future contamination of the groundwater by considering the vulnerability of an area before high-risk activities were allowed to take place. Information of non-point and point sources of potential pollutants, including population, livestock, pesticide usage, and industries, will be needed for the risk analysis of groundwater pollution.

In the regional screening process for the waste disposal site selection, only the pollution problem was considered. However, in the waste disposal siting, other factors that have not been considered, such as surface water, environmentally sensitive lands and population, must be considered.

The role of a Geographic Information Systems (GIS) in waste management is very significant, as many aspects of planning and operations are highly dependent on spatial data. In general, GIS plays a key role in maintaining account data to facilitate collection operations; customer service; analyzing optimal locations for transfer stations; planning routes for vehicles transporting waste from residential, commercial and industrial customers to transfer stations and from transfer stations to landfills; locating new landfills and monitoring the landfill. GIS is a tool that not only reduces the time and cost of site selection, but also provides a database for future monitoring programs for the site (Lee and others 1998).

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