Assessment of groundwater vulnerability using DRASTIC Model and GIS: A case study of two sub-districts in Banda Aceh city, Indonesia

I Machdar¹,³, T Zulfikar¹, W Rinaldi¹ and Y Alfiansyah²

¹ Chemical Engineering Department, Faculty of Engineering, Syiah Kuala University, Jalan Tengku Syech Abdur Rauf No. 7, Darussalam, Banda Aceh 23111, Indonesia
² Civil Engineering Department, Faculty of Engineering, Syiah Kuala University

E-mail: machdar@unsyiah.ac.id

Abstract. This present study assessed the groundwater vulnerability to protect aquifer in part of Banda Aceh City (the sub-district of Banda Raya and Lueng Bata), Indonesia. The study provides an additional tool for local planner and manager as for managing and protecting groundwater resources. The study area covers 1,164 ha and total population was estimated around 50,000 inhabitants. DRASTIC model in a GIS (Geographic Information System) environment was used in this study to generate vulnerability maps. The maps were created by applied seven criteria as standard in DRASTIC approach, i.e. depth to groundwater, recharge, aquifer type, soil properties, topography, impact of the vadose zone, and hydraulic conductivity. The vulnerability maps provides five categories of vulnerability, i.e. less, low, medium, high, and very high. It was found that the village areas, labelled with the high groundwater pollution potential, are mainly in the area of Lamlagang and the part of Geuce Kaye Jatoe and Geuce Komplek (Banda Raya sub-district) and the part of Batoh and Suka Damai (Lueng Bata sub-distric) This study prompts that the DRASTIC approach is helpful and efficient instrument for assessing groundwater vulnerability. The generated map can be an effective tool for local administrators in groundwater management as well.

1. Introduction

Surface water and groundwater are both essential sources of water supply and agriculture. Although surface water is used frequently as source of water supply due to its capacity and continuity, to date, groundwater is still a main source in several areas especially in developing countries. Issues related to groundwater mostly address to ecological degradation, salinization, and massive overuse [1, 2]. Groundwater pollution is problematic in Indonesia, for example, in Jakarta 45% of groundwater is already contaminated by faecal coliform [3]. Mainly, the sources of the contaminates originate from septic tank overflow [4], landfill leachate [5], industrial effluent [3].

Assessments and actions for groundwater pollution prevention are more effective ways than remedial ones. It is because a contaminated groundwater is very expensive to recover and take a few years back to origins. The investigation of potential for groundwater contamination or groundwater vulnerability has been intensively studied with a number of approaches during the past year [5-10].

³ To whom any correspondence should be addressed.
The DRASTIC method has been most frequently applied for mapping vulnerability in porous aquifer [11].

The objective of this study was to elaborate groundwater vulnerability in a shallow aquifer using DRASTIC model and a GIS software. Vulnerability means the sensitivity of an aquifer system to deterioration due to an external action [12].

2. Study Area
The study region in which the DRASTIC model and GIS was adapted is located in the Banda Aceh City, in the northwestern tip of the Sumatra island (Figure 1). The city of Banda Aceh is the provincial capital of Aceh Province, Indonesia, and is also center of education, commerce, and culture of the province. This region is characterized by a very flat with average elevation around 2 meters above sea level. The city comprises 9 sub-districts, i.e. Baiturrahman, Banda Raya, Jaya Baru, Kuta Alam, Kuta Raja, Lueng Bata, Meuraxa, Syiah Kuala, and Ulee Kareng.

In this study, the sub-district of Banda Raya and Lueng Bata was selected since it has been subject to inter-city terminal, warehousing, permanent settlement and business center since the development of Banda Aceh’s spatial planning in 2006. The sub-district of Banda Raya and Lueng Bata comprises 10 and 9 villages, respectively, and has a total surface of 1,164 ha. At present, the total population of the two districts is approximately 50,000 inhabitants. It is around 20% of the total population in the Banda Aceh City.

![Figure 1. Location Map of Banda Aceh City, boundary of the study area and monitoring wells.](image)

3. Experimental procedure and methodology

3.1. The DRASTIC index method
The DRASTIC is an approach developed by the US Environmental Protection Agency (USEPA) to provide a standardized evaluation of the potential for groundwater contamination [11]. The DRASTIC index or vulnerability rating present numerical ranking collective description of all the primary hydrological and geological considerations that influence groundwater flow through the vertical profiles of an area. In this approach, spatial collective data on depth to groundwater (D), recharge (R), aquifer type (A), soil properties (S), topography (T), impact of the vadose zone (I), and the hydraulic conductivity (C) are collected. For a defined area being investigated, each criterion is assigned a typical range and a rating relative value scale (r) from 1 to 10. In this scale, the higher values represent more sensitive area for contamination. These index criteria further are combined in an additive
equation. Moreover, each criterion is decided a weight factor (w), from 1 to 5, reveal the relative importance of each factor. In the end, the linear equation of the total impact criterion score as the DRASTIC index or vulnerability rating has the following formula:

$$D\text{RAS}TIC\ index\ (\text{vulnerability\ rating}) = D_Dw + R_Rw + A_Aw + SSw + TTw + I_Iw + C_Cw$$

where w is weight and r is rank.

In this formula, it applies four assumptions, i.e. (i) the contaminant is introduces at the ground surface; (ii) the contaminant is leached into the groundwater by precipitation; (iii) the contaminant is soluble; and (iv) the evaluated area is 40 ha or larger [11]. Obtained data is simplified by a GIS model interface. The GIS software was used in this study (ArcGIS) to prepare seven maps represent the seven criteria of DRASTIC. Individual map was classified and designated ratings and weighted according to DRASTIC standards [13] as shown in Table 1 and Eq. (1) was rewritten as follows:

$$D\text{RAS}TIC\ index\ (\text{vulnerability\ rating}) = 5D_D + 4R_R + 3A_A + 2S_S + TTw + 5I_I + 3C_C$$

Table 1. DRASTIC standard weight.

| Criteria                  | Weight |
|---------------------------|--------|
| Depth to groundwater (D)  | 5      |
| Recharge (R)              | 4      |
| Aquifer type (A)          | 3      |
| Soil properties (S)       | 2      |
| Topography (T)            | 1      |
| Impact of the vadose zone (I) | 5      |
| Hydraulic conductivity (C) | 3      |

4. Results and Discussion

4.1. Depth to groundwater (D)

Depth to groundwater is crucial criterion because it assigns the length that contaminant have to deliver prior to getting the groundwater. A deeper groundwater (low water table) is less vulnerable than high water table. In this study, the depth to groundwater was monitored from existing inhabitant shallow wells that scatter in the sub-district of Banda Raya and Lueng Bata. The total sampling comprises 55 shallow wells, 30 wells located in Banda Raya and 25 wells in Lueng Bata Sub-District. It was found that, depth to ground water was very shallow varies from 0.23 to 3.49 m. Accordingly, DRASTIC rating values were 9 and 10 for shallow and deep ground water, respectively [14] and affected by a weight of 5 (Figure 2).

4.2. Recharge (R)

Groundwater recharge is essential parameter for vulnerability because it is a route transportation of contaminant into aquifers. Net recharge criterion of this study is the sum of precipitation without taking in account of surface runoff and evapotranspiration. The source of recharge is the annual rainfall data taken from a local climatology station for 10-year period. The average annual recharge value was 130 mm, correspond to DRASTIC index of 8 (Figure 3).
4.3. Aquifer type (A)

The aquifer layer acts a main function over the pathway and leaching of contaminant. Normally, the larger the particle size distribution or the more permeable rock within the aquifer giving the higher the permeability and the lower the attenuation capacity. Aquifer layer information of this study was prepared using research data from the BGR Germany survey [15]. The main aquifer material layers in the study area are sand, gravel, and lime stone. The layers were assigned rating value from 2 to 8 and affected by a weight of 3 (Figure 4). A higher aquifer layer rating value implies higher permeability of the aquifer media and higher vulnerable potential.
4.4. Soil properties (S)
The soil layer is the upper part of the vadose zone which averages to a depth of 2 m or less from the ground surface. Soil properties affect groundwater pollution potential as they control the movement of air and contaminant [16]. Soil property information was evaluated from the map gathered from the BGR Germany survey [15]. The primary soil of the district of Banda Raya and Leung Bata is clay and sandy clay. DRASTIC standard ratings for this criterion vary between 1 and 5 (Figure 5).

4.5. Topography (T)
Topography (slope of an area) offers a high possibility for pollutant to infiltrate. It will be related to higher groundwater contamination. Moreover, topography controls the direction of contaminant flow. Areas with low land slope tend to hold water for longer time and enable a greater infiltration or recharge to generate a greater potential contaminant transportation. The topography map was obtained from the BGR Germany survey [15]. Slope variation in the study area is very small and is divide into two classes i.e. 2-6% and 6-12%. Areas of steadily low topography have higher vulnerability as contaminant can pool and more contaminant percolation into the groundwater. Topography ratings, according to standard DRASTIC for this area study are 5 to 9 [14] (Figure 6).

4.6. Impact of the vadose zone (I)
The vadose zone is an unsaturated layer above the water table. The impact of vadose zone on groundwater potential contamination is in principle identical to that of characteristic soil cover. The impact of vadose zone is a difficult phenomenon, depending on aquifer layers and topographic characteristics [17]. A higher impact of vadose zone if it is composed of porous soils. The data for impact of vadose zone was retrieved from identification and classification of the sub-surface geology map. The vadose zone were assigned rating value from 1 to 6 and affected by a weight of 5 (Figure 7). Higher rating value means higher vulnerability.
4.7. Hydraulic conductivity (C)

Hydraulic conductivity is the rate of water flow through horizontally an aquifer layer. Hydraulic conductivity of an aquifer is the ability of the aquifer to spread water depends on its permeability and the amount of saturated zone. As the conductivity increase, dispersion of contaminants in aquifer also increases. Accurate values of the hydraulic conductivity are not easy to obtain and it is also reflected as a drawback of the DRASTIC approach [8, 9]. In this study, the values of aquifer hydraulic conductivity was calculated based on pumping tests of existing inhabitant shallow wells in around study areas. The hydraulic conductivity values in the area were assigned rating value of 1 (0 – 4.08 m/d) and 2 (4.08 – 12.24 m/d) (Figure 8). An area with high conductivity is vulnerable to considerable contamination of groundwater. However, the contaminant can immigrate immediately through the
aquifer. This phenomenon is distinct from an aquifer which has an impermeable media, it can still water content in the presence of fractures [6].

![Figure 7. Vadose zone of the study area.](image)

![Figure 8. Hydraulic conductivity of the study area.](image)

4.8. Land use ($L$)

Land use information was integrated with DRASTIC standard criteria as an additional parameter to evaluate potential vulnerability in around of the study area. A weighting value equal to 5 was multiplied to the land use parameter [10, 18]. If the DRASTIC index in (Eq. 2) equal to DI, the resultant index includes land use parameter (MD) [19]:

$$MD = DI + L \cdot L_w$$  \hspace{1cm} (3)

where $L \cdot L_w$ is the land use index.
In order to attain detail vulnerable assessment, the land use parameter was included population density factor in the area investigated. The factor was assigned value of 5 (low, 487 – 1,945 people), 7 (medium, 1,956 – 3,405 people), and 9 (higher than 3,404 people) (Figure 9).

4.9. The DRASTIC values
The DRASTIC values describe the whole groundwater vulnerability and its individual criterion is useful to identify the contaminant pathway through aquifer in a study area. In the criterion of depth to groundwater rating layer, the study area with rating value of 9 and 10 cover 67.5% and 32.5%, respectively. The whole study area has a high net recharge rate, i.e. 8. For the aquifer layer result, only 33.8% of the study area contributes to groundwater pollution potential with rating value of 8. The prominent soil properties in the study area were covered by clay and sandy clay with rating value of 3 (95.3%) with low groundwater pollution potential and only 4.7% of the land area investigated contributes to contaminant pollution. In the criterion of topography rating layer, the low-lying area with the rating value of 9 was 75.3% coverage. The vadose zone media with the rating value 1 was 94.3% of the land area with meaning mainly low groundwater pollution potential. In hydraulic conductivity parameter, the rating layer of 1 covers 48.8% of the area study.

4.10. Groundwater pollution vulnerability
The groundwater vulnerability of the study area is present in Figure 10 based on overlay map of the DRASTIC map index (static vulnerability). The index values lay between 97 and 148. This range is classified on five categories of vulnerability, i.e. less (97-107), low (108-117), medium (118-127), high (128-139), and very high (140-148). The study illustrates that of the total 1,164 ha of the study area, it has 355 ha (30%), 411 ha (35%), 254 ha (22%), 115 ha (10%), and 30 ha (3%) categorized as less, low, medium, high, and very high groundwater pollution potential, respectively. The village areas, labelled with the high groundwater pollution potential, are mainly Lamlagang and part of Geuce Kaye Jatoe and Geuce Komplek (Banda Raya sub-district) and part of Batoh and Suka Damai (Lueng Bata sub-district).

Domestic wastewater discharge from inhabitant and small-scale business activities including schools, government offices, and mosques contribute to groundwater pollution potential as in the area is not installed an appropriate sewerage system. Analysis groundwater vulnerability of the area study using seven parameters of the DRASTIC approach combine with land use as additional parameter will give more clear picture of the area study sensitivity. Figure 11 presents map sensitivity analysis.
(dynamic vulnerability) that was performed by adding land use parameter. The index values of sensitivity lay between 101 and 188. This range is classified on five categories of vulnerability, i.e. less (101-118), low (119-134), medium (135-150), high (151-167), and very high (168-184). Of the total area, it was found that 11% and 2% of the area was high and very high category, respectively.

Figure 10. Static vulnerability map of the study area.

Figure 11. Dynamic vulnerability map of the study area.

5. Conclusions
The vulnerability maps of groundwater pollution potential based on the DRASTIC approach in the part of Banda Aceh, Indonesia were produced in an ArcGIS environment. These investigations can assist the Banda Aceh government official as an instrument for development of Banda Raya and Lueng Bata sub-district. The vulnerability map generated to this area study presents five categories. The map shows that only 115 ha or 10% and 30 ha or 3% of the total area study has high and very high vulnerability category, respectively. It was found that the village areas, labelled with the high
groundwater pollution potential, are mainly in the area of Lamlagang and the part of Geuce Kaye Jatoe and Geuce Komplek (Banda Raya sub-district) and the part of Batoh and Suka Damai (Lueng Bata sub-distric). Actually, the DRASTIC approach shows some weakness (the difficulty to validate vulnerability), however these generated maps could be use an additional tool by local planner.

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References

[1] Kagabu M, Shimada J, Delinom R, Nakamura T and Taniguchi M 2013 Hydrological Processes, 27 2591
[2] Kooy M 2014 Water Alternatives, 7 35
[3] Kees B 2016 Indonesia: Country water assessment Asian Development Bank ISBN: 978-92-9257-361-4 (Metro Manila, Philippines)
[4] Machdar I, Matsura N, Kodera H and Ohashi A 2014 J. of Water & Env. Tech 6 459
[5] Sholichin M 2012 Int. J. of Civil & Env. Eng. 12 74.
[6] Fritch T G, McKnight C L, Yelderman J C and Arnold A L 2000 Environ. Management 25 337.
[7] Srinivasamoorthy K, Chidambaram S, Sarma V S, Vasanthavigar M, Vijayaraghavan K, Rajivgandhi R, Anandhan P and Manivannan R 2009 Res J. of Environ and Earth Sci. 1 22
[8] Bastida M JJ, Arauzp M, Valladolid, M 2010 Hydrogeology Journal 18 681
[9] Lathamani R, Janardhana M R and Mahalingame B S 2015 Aquatic Procedia 4 1031
[10] Kihumba A M, Vanclooster M and Longo J N 2017 J. of African Earth Sci. 126 13
[11] Aller L, Bennet T, Lehr J H, Petty R J and Hackett G 1987 US EPA Report 600/287/035, U.S. Environmental Protection Agency
[12] Al-Zabet T 2002 Environmental Geology 43 203
[13] Aller L, Lehr J H and Petty R 1985 US, USEPA Report 600/02-85/018 U.S. Environmental Protection Agency
[14] Zhou Y 2008 Groundwater Monitoring, UNESCO-IHE, Delft, The Netherlands.
[15] Mangeonad 2007 Project Management of Georisk in NAD BGR Germany and Mining and Energy Department (NAD Province, Indonesia)
[16] Kiely G 1998 Environmental Engineering (Malaysia: McGraw-Hill)
[17] Rahman A 2008 Applied Geography 28 31
[18] Panagopoulos G, Antonakos A and Lambrakis N 2006 Hydrogeol J 14 894
[19] Secunda S, Collin M and Melloul A J 1998 J Environ Manage 54 39