Assessment of Groundwater Vulnerability using COP Method to Support the Groundwater Protection in Karst Area

E Yogafanny¹,²,* and D Legono¹

¹Civil and Environmental Engineering Department, Faculty of Engineering, Gadjah Mada University, Yogyakarta Indonesia, 565223
²Environmental Engineering Department, Faculty of Mineral Technology, University of Pembangunan Nasional “Veteran” Yogyakarta, Condongcatur, Yogyakarta, Indonesia 55283

*Corresponding Author: ekha.yogafanny@mail.ugm.ac.id

Abstract. The karst landform holds considerable water resource potential and is known for its underground rivers. On the other hand, the high porosity carbonate rocks on this landform cause the decrease of the natural protection function against groundwater pollution. Hence, the analysis of groundwater vulnerability in the karst area is prominent before making the spatial planning regulation. This recent study aimed to analyze the groundwater vulnerability in the karst area located in a part of Umbulrejo Village, Yogyakarta, Indonesia, and proposed action in groundwater protection. The method used in this research was based on the COP method. The data acquisition was conducted by survey method both for primary and secondary data. The COP (Concentration of flow, overlaying layers, and precipitation) analysis was supported by ArcGis software. The analysis of groundwater vulnerability showed that there were two vulnerability classes, i.e., very high (48.6%) and high (51.4%). These results were influenced mainly by the close distance of the recharge area to swallow holes and the lithology type (karst), which contributed to a very high value in reducing protection against groundwater. A proposed action to support groundwater protection is regulating the land utilization in the area of the settlements.

Keywords: COP method, groundwater vulnerability, karst

1. Introduction

The karst landform has unique hydrogeological conditions. This landform holds considerable water resource potential and is known for its underground rivers [1]. It causes karst aquifers to be one of the potential water resources in many countries in the world. This water resource appears as a spring that people widely use as water for domestic needs. Yogyakarta is one of the Provinces in Indonesia that has this landform, i.e., Gunung Kidul Regency.

On the other hand, landforms composed of carbonate rocks with an intensive dissolution process cause high secondary porosity values. It causes a decrease in the function of natural protection against groundwater pollution in karst areas [2]. The unique characteristics possessed by this karst aquifer system can result in a tended high level of vulnerability, both in terms of water quantity and quality. The karst aquifer system is very vulnerable to pollution compared to the non-karst aquifer system [3], [4]. Contaminants derived from the surface can quickly enter the groundwater through the ponor that is...
naturally exited in this landform. Pollutants easily enter the karst aquifer system due to the high permeability of the karst aquifer. It is caused by secondary porosity in the form of fractures [5].

It is crucial to analyze groundwater vulnerability in karst areas before carrying out spatial planning. It is to protect groundwater resources in the karst area due to the high potential for pollution of karst aquifers. Karst aquifer is vulnerable to contamination from human activities on the surface. These contamination processes are derived from the flow concentration to the swallow hole or sinking stream, the high porosity carbonate rock, and the thin soil or cover layer [6]

Regarding the importance of protecting groundwater resources, and since groundwater remediation is costly, the preventive strategy is paramount in any decision-making related to water resource management [2]. One of the preventive strategies that can be done is the analysis of groundwater vulnerability to contamination. The concept of groundwater vulnerability is to identify the zone and class of groundwater as a resource against contamination. It is necessary to determine the degree of groundwater vulnerability in each zone spatially [6]–[8]. The groundwater vulnerability method generally used is based on the definition of intrinsic vulnerability, where this vulnerability is determined based on contamination generated by human activities. Intrinsic vulnerability analysis involves the geological, hydrological, and hydrogeological characteristics of an area but does not depend on the nature of the pollutant [8].

Many methods and researches have been conducted to assess the groundwater vulnerability to pollution, i.e., DRASTIC [9]–[12], GOD [13], [14], SINTACS [15], etc. These methods have been developed and used to identify the groundwater vulnerability in the porous aquifer. On the other hand, some methods have been proposed, i.e., EPIC [16]–[19], PI [17], APLIS [20]–[22], and COP [6], [9], [19], [23]–[25] to analyze the groundwater vulnerability in karst areas which has the typical hydrogeological condition due to the carbonate overlying rocks. According to the potentially high vulnerability of the groundwater resources, an analysis of groundwater intrinsic vulnerability in the karst area is very important to support the government in managing the land use and environment.

The karst area conducted in this study is in the Part of Umbulrejo Village, Gunung Kidul Regency. This area is interesting because there are two landforms in this village-level administrative unit, i.e., karst and non-karst landform. On the other hand, environmental management needs to be started at the smallest community level, such as RT, RW, and Hamlet. By knowing the zonation of groundwater vulnerability in karst areas located in a part of Umbulrejo Village, the land use or land utilization management can be proposed to protect groundwater from contamination due to human activities. Human activities contaminating groundwater in karst areas include temporary garbage dumps, not tightly closed toilets, cattle pens without proper sanitation, etc.

This recent study was aimed to analyze the groundwater vulnerability in the karst area located in a part of Umbulrejo Village, Yogyakarta, Indonesia. The groundwater vulnerability map can be used as a reference to support groundwater protection in the research area.

2. Materials and Method
This research is located in a part of Umbulrejo Village, Gunung Kidul Regency, Yogyakarta Special Province. The research area consisted of seven hamlets, namely Sanggrahan Hamlet, Wirik Hamlet, Sladi Hamlet, Dlisen Hamlet, Plalar Hamlet, Wanglu Hamlet, and Blimbing Hamlet. The map of administration and land use can be seen in figure 1, which shows that the research area is dominated by moorland use. In general, the research area is at an altitude of 200 m to 350 m. Most of the settlements are located in the southern part of the study area. At the same time, the moor is evenly distributed throughout the study area.

Physiographically, the research area is included in the sub-zone of the Gunungsewu karst area in the Southern zone. Regionally, the research area is included in the Geological Map of Surakarta 1408-3 & Giritontro 1407-6 Scale 1: 100.000 and in the Gunungsewu sub-zone. The research area consists of the Wonosari Formation with rock units in the form of non-clastic limestones such as crystalline limestone, foraminifera limestone, and reef limestone with an insert in the form of rocks that have non-impermeable properties.
Figure 1. Map of Administration and Landuse in the Part of Umbulrejo Village

The COP method applied to assess a zonation of groundwater vulnerability was operated using a GIS (Geographic Information System) application in the form of ArcGIS software. ArcGIS software is used to analyze and visualize the zonation of groundwater vulnerability in the study area. The COP method was chosen based on previous research, which found that this method was quite effective and reliable in assessing the groundwater vulnerability, especially in karst areas [2], [23].

The COP method is developed to analyze the intrinsic susceptibility of karstic aquifers (carbonate aquifers). Intrinsic vulnerability is vulnerability based on the hydrogeological characteristics of an area but does not depend on natural or artificial pollutants. The COP method is an acronym for Concentration of flow (C), Overlaying layers (O), and Precipitation (P) which are also three determinants of the level of groundwater vulnerability [8]. Two conditions are needed to assess intrinsic susceptibility in a study area using the COP method: firstly, contaminants depend on the characteristics of water moving through the aquifer, and secondly, contaminants can infiltrate from the surface carried by rainfall agents [26]. The results of the groundwater vulnerability using this method were 5 class classifications, namely very low, low, moderate, high, and very high.

2.1. The C factor (Concentration of Flow)
The C factor reflects the surface conditions that control water flowing into the infiltration zone. The value or scoring for factor C can be seen in Table 1. There are two scenarios in determining this C factor, i.e., 1) the swallow hole recharge area and 2) the rest of the area. In the first scenario, all water flowing on the surface of the catchment area is considered to flow into the sinkhole. The values of the C factor depend on the distance between the recharge area and the ponor/sinkhole (dh) as well as the sinking stream (ds) and depend on the topographic characteristics (slope (s) and vegetation (v)). The value of the C factor for the first scenario is obtained by multiplying all parameter values as in Equation 1.
### Table 1. Scoring value of C Factor

| Factor C | Sub-factor | Variable | Value |
|----------|------------|----------|-------|
| C (Scenario 1) | Distance to donor (dh) | ≤ 500 | 0 |
| | | (500-1000) | 0.1 |
| | | (1000-1500) | 0.2 |
| | | (1500-2000) | 0.3 |
| | | (2000-2500) | 0.4 |
| | | (2500-3000) | 0.5 |
| | | (3000-3500) | 0.6 |
| | | (3500-4000) | 0.7 |
| | | (4000-4500) | 0.8 |
| | | (4500-5000) | 0.9 |
| | | > 5000 | 1 |
| C (Scenario 1) | Distance to the sinking stream (ds) | < 10 m | 0 |
| | | 10-100 m | 0.5 |
| | | > 100 m or no sinking stream | 1 |
| C (Scenario 1) | Slope and vegetation (sv) | ≤ 8% | 1 |
| | | (8-31)% Vegetation | 0.95 |
| | | (8-31)% No Vegetation | 0.9 |
| | | (31-76)% Vegetation | 0.85 |
| | | (31-76)% No Vegetation | 0.8 |
| | | >76% | 0.75 |
| C (Scenario 2) | Karst Feature (sf) | Developed karst | No surface layer | 0.25 |
| | | | Permeable surface layer | 0.5 |
| | | | Impermeable surface layer | 0.75 |
| | | Scarcely developed or dissolution | No surface layer | 0.5 |
| | | | Permeable surface layer | 0.75 |
| | | | Impermeable surface layer | 1 |
| | | Fissured carbonate | No surface layer | 0.75 |
| | | | Permeable surface layer | 0.75 |
| | | | Impermeable surface layer | 1 |
| | | Non-karstic terrain | No surface layer | 1 |
| | | | Permeable surface layer | 1 |
| | | | Impermeable surface layer | 1 |
| C (Scenario 2) | Slope dan Vegetasi (sv) | ≤ 8% | 0.75 |
| | | (8-31)% Vegetation | 0.8 |
| | | (8-31)% No Vegetation | 0.85 |
| | | (31-76)% Vegetation | 0.9 |
| | | (31-76)% No Vegetation | 0.95 |
| | | >76% | 1 |

**Score 'C'**

(0 – 0.2) Very high

(0.2 – 0.4) high

(0.4 – 0.6) Moderate

(0.6 – 0.8) Low

(0.8 – 1) Very low

**Source:** [6]
Factor $C = dh \cdot ds \cdot sv$ \hspace{1cm} (1)

The second scenario, the area where runoff or infiltration may occur, depending on the slope ($s$) and vegetation ($v$), especially on surface characteristics (karst features ($sf$) and permeability). In both scenarios, slope and vegetation are considered, but in different ways. The value of factor $C$ in the second scenario is obtained by multiplying all parameter values in Equation 2.

Factor $C = sf \cdot sv$. \hspace{1cm} (2)

| Factor O | Sub-factor | Variables | Value |
|----------|------------|-----------|-------|
| Soil [O_s] | Texture and thickness | No soil | 0 |
| | | Loam, 0.5 – 1 m | 1 |
| | | Sandy, < 0.5 m | 1 |
| | | Loam, >1 m | 2 |
| | | Sandy, 0.5 – 1 m | 2 |
| | | Silty, < 0.5 m | 2 |
| | | Sandy, >1 m | 2 |
| | | Silty, 0.5 – 1 m | 3 |
| | | Clayey, < 0.5 m | 4 |
| | | Silty, >1 m | 4 |
| | | Clayey, 0.5 – 1 m | 5 |
| | | Clayey, >1 m | 5 |

| Lithology [O_L] | Lithology and fracture | Clays | 1500 |
| | | Silts | 1200 |
| | | Marls, metapelites, and igneous rock | 1000 |
| | | Marly limestone | 500 |
| | | Fissured metapelites and igneous rock | 400 |
| | | Conglomerates and breccias | 100 |
| | | Sandstones | 60 |
| | | Fissured conglomerates and breccias | 40 |
| | | Sands and gravels | 10 |
| | | Permeable basalt | 5 |
| | | Fissured carbonated rocks | 3 |
| | | Karstic rocks | 1 |

| Confining condition | Semi-confined | 1.5 |
| | Unconfined | 1 |

| Indeks Layer (ly.m) | Value |
|---------------------|-------|
| (0-250) | 1 |
| (250-1000) | 2 |
| (1000-2500) | 3 |
| (1000-2500) | 4 |
| >10000 | 5 |

Score ‘O’

| Score | Protection Value |
|-------|------------------|
| 1 | Very low |
| 2 | Low |
| (2 – 4) | Moderate |
| (4 – 8) | High |
| (8 – 15) | Very high |

*Source: [6]*
2.2. The O factor (Overlaying layers)
The O factor refers to the protection of the unsaturated zone of the aquifer against contaminants. This value demonstrates the ability of the unsaturated zone, through various processes, to filter or reduce contamination and thereby reduce its pollution effects. The value or scoring of factor O can be seen in Table 2. Two layers are used to evaluate the O factor, each corresponding to a layer in the unsaturated zone with different hydrogeological properties. The two layers are as follows:

- Soil [Os], related to the biologically active part of the unsaturated zone. One of the main features that characterize this aquifer zone is the self-cleaning process. Two possible parameters or variables for soil factor evaluation are texture and thickness.

- The lithology [OL] is related to the capacity of the water infiltration level at each layer of rocks in the unsaturated zone. For quantification, three parameters were adopted, namely: lithology and fracture (ly); thickness of each layer (m); and the confining condition of the aquifer (cn). The OL value is calculated by Equation 3.

\[ O_L = [\Sigma (ly.m) \cdot cn] \]  

To O Factor is calculated by Equation 4.

\[ O \text{ Factor} = [O_S] + [O_L] \]  

2.3. The P factor (Precipitation)
The P factor is related to the characteristics of the rainfall or precipitation as an agent (water) to transport the contaminants through the unsaturated zone. The effect of rainfall on vulnerability is not as significant as flow concentration, and the value of the P factor ranges from 0.4 to 1. The main significance of the P Factor is that it is a parameter developed to distinguish zones with varying degrees of rainfall. The value or scoring for the P factor can be seen in Table 3. The P factor modifies the protective capacity of the aquifer depending on the quantity of precipitation \( P_O \) and the temporal distribution of precipitation \( P_I \), as can be seen in Equations 5 and 6. The greater capacity of the transport agent (water) to carry contaminants towards the aquifer implies a higher vulnerability.

\[ Temporal \ distribution = \frac{precipitation \ (mm/year)}{no. \ of \ rainy \ days} \]  

\[ P \text{ Factor} = [P_O] + [P_I] \]  

| Factor P | Sub-factor | Variables | Value |
|----------|------------|-----------|-------|
| Precipitation (mm/year) | > 1600 | 0.4 |
| | (1200 – 1600) | 0.3 |
| | (800 – 1200) | 0.2 |
| | (400 – 800) | 0.3 |
| | ≤ 400 | 0.4 |
| Temporal distribution of precipitation (mm/day) | <10 | 0.6 |
| | (10 – 20) | 0.4 |
| | >20 | 0.2 |

Score ‘P’  

| 0.4 – 0.5 | Very high |
| 0.6 | High |
| 0.7 | Moderate |
| 0.8 | Low |
| 0.9 – 1 | Very low |

Source: [6]
2.4. Total COP score
All factors obtained from the previous calculation were multiplied to analyze and evaluate the groundwater vulnerability based on the formula given in equation 7. Where C is the total of factor C (sv . dh . ds)/(sv . sf), O is the total of factor O (OL + OS), and P is the total of factor P (PQ + Pt).

\[ \text{COP index} = C \times O \times P \]  

The multiplication of three factors gains the total vulnerability index. The value of vulnerability given by the COP method ranged from 0 – 15 that can be seen in Table 4. This value was classified into five vulnerability classes, i.e., very high, high, moderate, low, and very low [6]. Vulnerability classes of very high and high mainly depended on the influence of the C factors on carbonate rocks, while the P factor has a lesser degree of influence [6]. Vulnerability assessment using the COP method is processed using ArcGis 10.7 software by overlying three maps from each factor: the C factor map, the O factor map, and the P factor map. The results of combining the three maps produce the zonation of groundwater vulnerability in the study area.

| COP Index | Vulnerability Classes |
|-----------|-----------------------|
| (0 – 0.5) | Very high             |
| (0.5 – 1) | High                  |
| (1 – 2)   | Moderate              |
| (2 – 4)   | Low                   |
| (4 – 15)  | Very low              |

**Tabel 4. The vulnerability classes of COP Method**

Source: [6]

3. Result and Discussion

3.1. Zonation of Groundwater Vulnerability
The first scenario was applied to analyze the C factor where the concentrated runoff from the recharged area flowed into the ponor. On the other hand, the second scenario was applied in the rest of the research area. From the first scenario analysis, the distance between the recharge area and the ponor/lake was in the range of 500 – 1000 m. Thus the total score of the first scenario was 0 – 0.1 and categorized as very high. The analysis for the C factor in the rest of the area (southwestern part) referred to the second scenario, classified as the absence of developed karst and thus scored 0.25. The slope was < 8% with no vegetation thus has scored 0.75. The total score of the second scenario in the southwestern part was 0.1875 and categorized as a very high reduction of protection. On the other hand, this scenario was applied in the northern and southeastern parts of the study area. These areas were classified into permeable developed karst (0.5) and 8 – 31 % land slope with high vegetation (0.8). The total score of the second scenario in these areas was 0.4 and categorized as a high reduction of protection. The map of the C factor is presented in Figure 2.

The analysis of O factor shows that the sub-variable soil (Os) in general is loam-textured with a thickness variation <0.5 m with a score of 1, 0.5 – 1 m with a score of 2, and a thickness of > 1 m with a score of 3. The rock type (Ol) is carbonate rock and most of which have a rock thickness of 6 – 10 m with a score of 1. The assessment of the O factor regarding the value protection of groundwater was moderate, as presented in Figure 3. The moderate value was more influenced by the type of rock dominated by karst rocks. Hence, the level of groundwater protection against contamination is low. Although the cover layer variable is in soil, which tends to have a clayey loam texture and can function as a water rate inhibitor due to its low permeability value, the dominant infiltration process is through the ponor, and the Ol value became dominant.

The analysis for the P factor shows that the value of annual precipitation calculated from 2009 to 2019 is 1848 mm/year, so it is classified as >1600 mm/year with a score of 0.4. The temporal distribution of precipitation is calculated based on dividing the amount of annual precipitation by the total number
of rainy days, and the result is 16.3 mm/day which falls into the 10 – 20 classification with a score of 0.4. The results of the assessment of the P factor on the reduction of protection are low for the entire area of the study area, as shown in Figure 3.

Rainfall helps identify contaminants carried by surface runoff to karst groundwater systems. Therefore, the value of rainfall and the temporal distribution of rain will determine the ability to carry contaminants that flow to the karst groundwater system in the study area. The analysis results indicate that the precipitation (P) factor in the study area was ns that rainfall and temporal distribution in the study area reduce protection against pollution.
All three factors were analyzed and combined using the overlay method in ArcGIS, and the results of the vulnerability zones were obtained. The vulnerability zones based on the COP method were two classes, namely high and very high which are presented in Figure 4 and Table 5. The area of the vulnerability zone classified as high is 51.4%, and very high is 48.6% of the total area.

![Map of groundwater vulnerability](image)

**Figure 4.** Map of groundwater vulnerability

| Class of Vulnerability | Area (ha) | Percent of the total area (%) | Area distribution (Hamlet) |
|------------------------|-----------|-------------------------------|---------------------------|
| High                   | 250.19    | 51.4%                         | Plalar, Sladi, Sanggrahan Blimbing |
| Very High              | 236.88    | 48.6%                         | Silingi, Wirik, Sladi, Dlisen |

The result of the groundwater vulnerability map obtained shows that the percentages of the area with very high and high vulnerability classes were almost equal to the study area, i.e., 48.6% and 51.4%, respectively. Several factors influence the results of the groundwater vulnerability map that has been made. The main factor was the ponors and lokva in the lithology of carbonate or karst rock which contributed to a very high value in reducing protection against groundwater. Based on this, it can be assumed that the level of vulnerability for karst areas has a reasonably low score, resulting in a very high vulnerability class. The variable that influenced the high vulnerability was the karstic feature, the surface layer, and a relatively steep slope.

### 3.2. Proposed Action in Groundwater Protection

All water resources must be managed in a comprehensive and integrated action. It is proposed to realize sustainable water use for the prosperity of the people in the area. One of the water sources, groundwater, should be managed using the principle of integration with the surface water system. Groundwater management is based on groundwater management policies and strategies. The groundwater policy itself is shown as a direction in conducting groundwater conservation, utilizing groundwater, controlling the...
destructive power of groundwater, and a groundwater information system prepared by taking into account the condition of groundwater in an area. Groundwater management policies are formulated and stipulated in an integrated manner of water resources management [27].

Meanwhile, the groundwater management strategy itself is a basic framework for designing, implementing, monitoring, and evaluating groundwater conservation activities, utilizing groundwater, and controlling the destructive power of water. Groundwater management strategies are compiled and stipulated in an integrated manner in a river area's water resources management pattern. Groundwater conservation implementation is based on the groundwater management plan that has been made. Groundwater conservation is carried out comprehensively and includes groundwater recharge areas and discharge areas. The efforts made are the protection and preservation of groundwater, quality management, and control of groundwater pollution [27], [28].

One of the strategies was controlling groundwater pollution. The analysis of groundwater vulnerability can be used as a scientific basis in decision-making strategies to protect the groundwater. According to the current condition in the study area, a proposed action to support groundwater protection is regulating land utilization in settlements. Some of the settlement areas in the study area are not fully used as residential houses. Many residents use their yards as livestock land with a poor sanitation system. This area is included in the very high vulnerability class based on hydrogeological conditions and groundwater vulnerability maps. Accumulated animal manure may infiltrate the groundwater through the fracture of the karst rock with a carrier agent in the form of rainwater or surface runoff. The livestock activities should be carried out using good waste management.

4. Conclusion

The study of groundwater vulnerability using the COP method found that in the part of Umbulrejo Village, the groundwater has a very high (48.6% of the total area) and high (51.4% of the total area) vulnerability to contamination. These results were influenced mainly by the close distance of the recharge area to swallow holes and the lithology type (karst). Since the vulnerability class is very high, especially in the settlement areas, a proposed action to support groundwater protection regulates land utilization in the settlements. The livestock activities should be carried out using good waste management.

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References

[1] H. a. Basha and C. a. Zoghbi 2018 Simplified Physically Based Models for Pressurized Flow in Karst Systems Water Resour. Res. vol 54 no 10 pp 7198–7215 doi: 10.1029/2018WR023331.

[2] E. Hadžić, N. Lazović, and a. Mulaomerović-Šeta 2015 The Importance of Groundwater Vulnerability Maps in the Protection of Groundwater Sources Key Study: Sarajevsko Polje Procedia Environ. Sci. vol 25 pp 104–111 doi: 10.1016/j.proenv.2015.04.015

[3] W. Zhou and B. F. Beck 2011 Karst Management

[4] F. Guo and G. Jiang 2011 Karst Groundwater Management through Science and Education,” Open J. Geol. vol 01 no 03 pp 45–50 doi: 10.4236/ojg.2011.13005

[5] C. Leibundgut 1998 Vulnerability of karst aquifers IAHS-AISH Publ. vol 247 no 247 pp 45–60

[6] J. M. Vías, B. Andreo, M. J. Perles, F. Carrasco, I. Vadillo, and P. Jiménez 2006 Proposed method for groundwater vulnerability mapping in carbonate (karstic) aquifers: The COP method Hydrogeol. J. vol 14 no 6 pp 912–925 doi: 10.1007/s10040-006-0023-6

[7] D. Machiwal, M. K. Jha, V. P. Singh, and C. Mohan 2018 Assessment and mapping of groundwater vulnerability to pollution: Current status and challenges Earth-Science Rev. vol 185 August pp 901–927 doi: 10.1016/j.earscirev.2018.08.009
ICWRDEP 2021
IOP Conf. Series: Earth and Environmental Science 930 (2021) 012036
doi:10.1088/1755-1315/930/1/012036

[8] D. Daly et al. 2002 Main concepts of the 'European approach' to karst-groundwater-vulnerability assessment and mapping Hydrogeol. J. vol 10 no 2 pp 340–345 doi: 10.1007/s10040-001-0185-1

[9] T. O. Abdullah, S. S. Ali, N. a. Al-Ansari, and S. Knutsson 2016 Groundwater Vulnerability Using DRASTIC and COP Models: Case Study of Halabja Saidsadiq Basin, Iraq Engineering vol 08 no 11 pp 741–760 doi: 10.4236/eng.2016.811067

[10] A. M. Al-Rawabdeh, N. a. Al-Ansari, A. a. Al-Taani, and S. Knutsson 2013 A GIS-Based Drastic Model for Assessing Aquifer Vulnerability in Amman-Zerqa Groundwater Basin, Jordan Engineering vol 05 no 05 pp 490–504 doi: 10.4236/eng.2013.55059.

[11] T. T. Putranto 2019 Studi Kerentanan Airtanah Terhadap Pencemaran Dengan Menggunakan Metode Drastic Pada Cekungan Airtanah (Cat) Karanganyar-Boyolali, Provinsi Jawa Tengah J. Ilmu Lingkung vol 17 no 1 p 159 doi: 10.14710/jil.17.1.159-171

[12] S. A. Oke and F. Foure 2017 Guidelines to groundwater vulnerability mapping for Sub-Saharan Africa Groundw. Sustain. Dev. vol 5 no March pp 168–177 doi: 10.1016/j.gsd.2017.06.007

[13] K. Kadour, B. El Hacen, D. Hlima, and D. Yasmina 2018 Groundwater vulnerability assessment using GOD method in Boulimat coastal District of Bejaia area North east Algeria J. Bio. Env. Sci, vol 109 no 3 pp 109–116

[14] B. T. Sukmawati Rukmana, W. S. Bargawa, and T. A. Cahyadi 2020 Assessment of Groundwater Vulnerability Using GOD Method IOP Conf. Ser. Earth Environ. Sci. vol 477 no 1 doi: 10.1088/1755-1315/477/1/012020

[15] S. Linggasari, T. A. Cahyadi, and R. Ernawati 2019 Overview Metode Perhitungan Kerentanan Airtanah Terhadap Rencana Penambangan Pros. Nas. Rekayasa Teknol. Ind. dan Inf. XIV no. 1451 pp 123–129

[16] A. Vogelbacher, N. Kazakis, K. Voudouris, and S. Bold 2019 Groundwater vulnerability and risk assessment in a karst aquifer of Greece using EPIK method Environ. - MDPI vol 6 no 11 pp 1–16 doi: 10.3390/environments6110116

[17] N. Goldscheider 2005 Karst groundwater vulnerability mapping: Application of a new method in the Swabian Alb, Germany Hydrogeol. J. vol 13 no 4 pp 555–564 doi: 10.1007/s10040-003-0291-3.

[18] R. El Bardai, K. Targuisti, and K. Aluni 2015 A Contribution of GIS Methods to Assess the Aquifer Vulnerability to Contamination: A Case Study of the Calcareous Dorsal (Northern Rif, Morocco), " J. Water Resour. Prot. vol 07 no 06 pp 485–495 doi: 10.4236/jwarp.2015.76039

[19] J. Doummar, A. Margane, T. Geyer, and M. Sauter 2012 Protection of Jeita Spring: Vulnerability Mapping Using the COP and EPIK Methods October p 42

[20] N. . Pertiwi, E. . Mayasari, and E. W. . Hastuti 2015 Pemanfaatan Sistem Informasi Geografis (SIG) Terhadap Zonasi Kerentanan Airtanah Menggunakan Metode APLIS Pada Kawasan Karst Gudawang Desa Argapura, Kabupaten Bogor Semin. Nas. AVoER XI, Fak. Tek. Univ. Sriwij pp 266–271

[21] A. P. Widiastuti 2012 Zonasi Kerentanan Airtanah Bebas terhadap Pencemaran dengan Metode APLIS di Kecamatan Wonosari Kabupaten Gunungkidul J. Bumi Indones. vol 1 no 2 pp 38–46

[22] H. Farfán, J. L. Corvea, and I. De Bustamante 2010 Sensitivity analysis of APLIS method to compute spatial variability of karst aquifers recharge at the national park of viñales (Cuba) Environ. Earth Sci. pp 19–24 doi: 10.1007/978-3-642-12486-0_3

[23] E. Yogafanny, T. T. Anastasia, and Vindy Fadia Utama 2020 Zonasi Kerentanan Air Tanah menggunakan Metode COP dan Aplis di Daerah Aliran Sungai Gremeng Desa Umbrelore Ponjong, Gunung Kidul JPPDAS vol 4 no 2 pp 103–120

[24] B. Andreo, N. Ravbar, and J. M. Vías 2009 Source vulnerability mapping in carbonate (karst) aquifers by extension of the COP method: Application to pilot sites Hydrogeol. J. vol 17 no 3 pp 749–758 doi: 10.1007/s10040-008-0391-1
[25] G. Sappa, F. Ferranti, and F. M. De Filippi 2017 Vulnerability Assessment of The Karst Aquifer Feeding The Pertuso Spring (Central Italy): Comparison Between Different Applications of Cop Method Int. J. Eng. Sci. Res. Technol. vol 6 no 6
[26] F. Zwahlen 2003 COST Action 620 Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers Final Report Water p 297
[27] Indonesian Government 2019 Undang-undang RI No 17 tahun 2019 tentang sumber daya air no. 011594 pp 1–50
[28] O. A. Illiyin and F. Faris 2017 Geotechnical Investigation and Numerical Analysis of Rockfall in South Coast of Gunung Kidul Regency J. Civ. Eng. Forum vol 3 no 1 pp 45–50 doi: 10.22146/jcef.26595