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GROUNDWATER VULNERABILITY OF PANDAK AND BAMBANGLIPURO, YOGYAKARTA SPECIAL PROVINCE, INDONESIA

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Abstract

The study of intrinsic vulnerability of groundwater was generated in order to delineate groundwater protection zone in Pandak and Bambanglipuro, Indonesia, whose mainly water supply is from groundwater. Two methods of vulnerability mapping are chosen for the evaluation; DRASTIC method and Hoelting method. The resulted maps conducted from these method are validated using the actual contaminant concentration through the impact of on-site sanitation, for instance nitrate as it is proved to be very stable contaminants in groundwater. Considered in different hydrogeological setting, these two methods have produced various results at the certain site. However, its reliability has been drawn upon the nitrate concentration at the study areas.

Keywords: *Intrinsic groundwater, vulnerability, DRASTIC, Hoelting methods, nitrate contamination.*

1 Introduction

The concept of groundwater vulnerability is derived from the assumption that the physical environment may provide some degree of protection of groundwater against natural and human impacts (Vrba and Zaporozec, 1994). Technically, there are two types of vulnerability; intrinsic vulnerability and specific vulnerability. According to Vrba and Zaporozec (1994), the term intrinsic vulnerability is used to define the vulnerability of the groundwater to contaminants generated by human activity as a function of natural factors such as hydrogeological factors, hydrology, the overlying soil and geological material. While the term specific vulnerability is used to define the vulnerability of groundwater to a particular contaminant or grounp of contaminants by taking account the contaminant properties and their relationship with the various components of intrinsic vulnerability.

Many intrinsic vulnerabilities methods have been developed in the past two decades but basically there are only three mainly groups of these techniques referred as hydrogeological complex and setting methods (HCS), parametric methods (included matrix systems (MS), rating systems (RS), and point count system models (PCSM)), and analogical relation and numerical model (AR). The intrinsic methods applied in the case study are both from the point count system model. DRASTIC method is a method developed for the U.S. Environmental Protection Agency (EPA) by Aller *et al.* (1985, vide Aller *et al.*, 1987). In the other hand, Hoelting method, which takes the unsaturated zone into consideration, was developed by the Geological Survey of the individual states of the Federal Republic of Germany in 1995 (Voigt *et al.*, 2004).

Since vulnerability is not an absolute characteristic but subjective, relative, non-measurable, dimensionless property (Vrba and Zaporozec,

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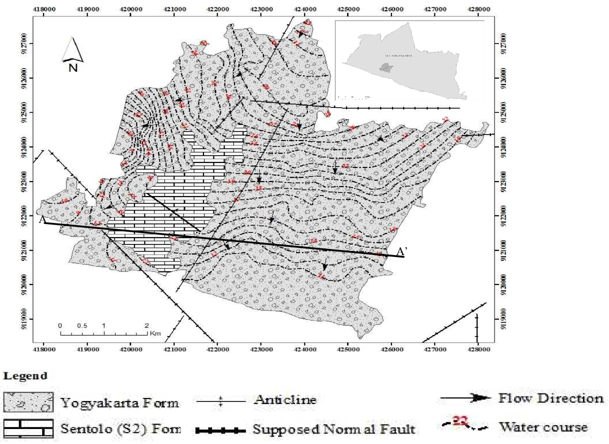

Figure 1: Geology and hydrogeological of the study area (adapted from Putra, 2003 and MacDonald & Partners, 1984).

1994), the reliability of the each vulnerability maps is still be a topic to be discussed among hydrogeologist. From many research works, Gugo and Dassargues (2000) has suggested that the only way of gaining confidence in vulnerability is by comparing the results of various techniques and analyzing their consistency with the actual contaminant at the study area.

The main objective of this study is, (1) to determine the intrinsic vulnerability of groundwater in two study areas using two different methods; (2) to evaluate the suitability of the method for the study areas.

2 Study Area

2.1 Climate

The study areas are located in Pandak and Bambanglipuro, Bantul Regency, Yogyakarta Special Privince, Indonesia. It lies between 418000 to 428200 East and 9118000 to 9128000 North (see Figure 1). Geomorphologically, the study area is generally flat down to the south. However, there is a small hill at the central part of Pandak whose elevation varied from 25 to 62.5 m above sea level.

Situated in the tropical area, its climate characterized by a warm monsoon climate with temperature varies from 25.78 °C (in April) to 27.65 °C (in March) (PSDA, 2008). During 10 years period (2000-2009), the annual rainfall ranges between 1700 mm/a to almost 2000mm/a with the real evapotranspiration estimated from 1300 to 1450 mm/a.

2.2 Geology and Hydrogeology

According to the regional geological context, the study areas are located in southern part of Yogyakarta basin. It consists of only two formation; Yogyakarta Formation which is a result of Merapi Volcano ejecta in Quaternary succession and composes of sand, gravel, silt and clay; Sentolo Formation, occurred in Tertiary succession and consists of marl, limestone and marly limestone (see Figures 1, 2) (Putra, 2003, MacDonald & Partners, 1984).

The recharge of the groundwater in the study areas is mainly by infiltration of precipitation while the urban or artificial recharge was overlooked due to its groundwater usage cycle. This cycle is described from the direct extraction of the water and directly use as main supply then depose back directly though on-site sanitation and finally begin with another extraction. Confirmed by Putra (2007) that the groundwater recharge in Yogyakarta can be primarily determined by considered only the estimation if groundwater recharge due to precipitation, with reduction of actual evapotranspiration and runoff.

2.3 Application of DRASTIC Method to the Study Area

DRASTIC is a point count system method developed by Aller *et al.* (1987) for Environmental Protection Agency (EPA). DRASTIC is an acronym of Depth to water (D), Net Recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of vadose zone (I), Hydraulic Conductivity of aquifer (C). The degree of vulnerability is defined according to the DRASTIC index value which represents the pollution potential of groundwater to be polluted. The DRASTIC index can be calculated using equation below:

$$\begin{aligned}\text{DRASTIC index} &= 5\times D_R + 5\times R_R + 3\times A_R\\ &\quad +2\times S_R + 1\times T_R + 1\times I_R\\ &\quad +3\times C_R\end{aligned}$$

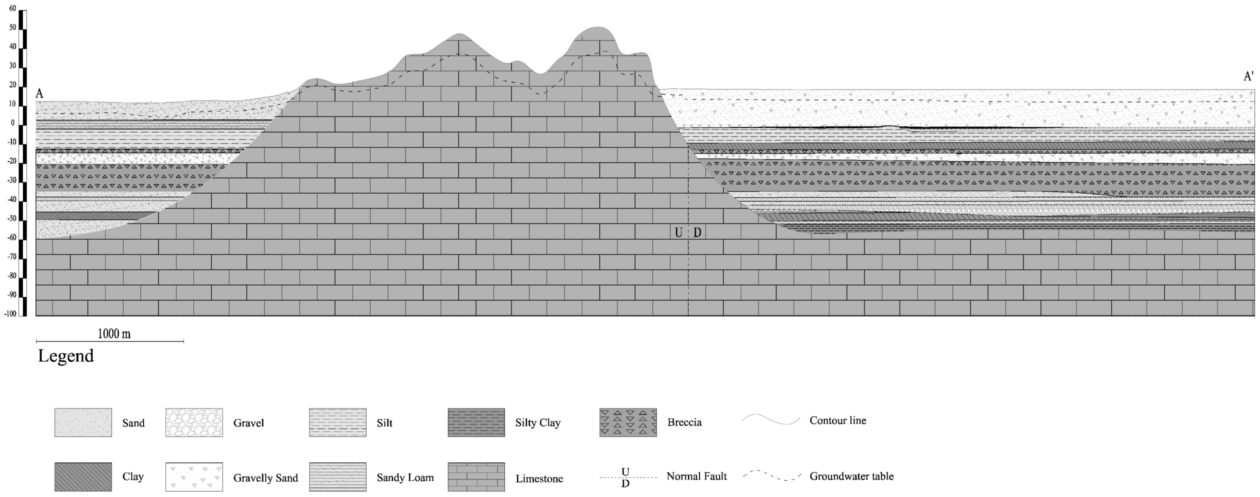

Figure 2: Stratigraphy cross section within the study area.

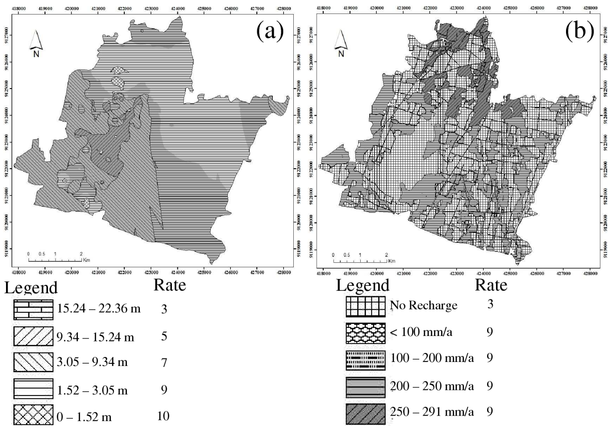

Figure 3: a) Depth to water and b) Net recharge ranges and corresponding rating according to DRASTIC in the study areas.

2.4 Depth to Water (D)

Depth to groundwater refers either to the depth to the water surface in an unconfined aquifer or to the top of the aquifer where the aquifer is confined (Aller *et al.*, 1987). From 79 dug-wells measurement at the field within the grid 250m × 250m, the map of depth to groundwater is then created and transformed into digital elevation model on the basis of defined ranges of DRASTIC (see Figure 3a).

2.5 Net Recharge (R)

According to Aller *et al.* (1987), net recharge indicates the amount of water per unit area of land which penetrates the groundwater surface and reached the water table. As mentioned above, the groundwater recharge in study areas is primarily from the natural infiltration from precipitation. Though, runoff is very important within these areas due to its lithology and land-use type. The highest recharge in the area is about 290 mm/a (see Figure 3b).

2.6 Aquifer Media (A) and Hydraulic Conductivity (C)

Based on Aller *et al.* (1987), aquifer media refers to the consolidated or unconsolidated medium which serves as an aquifer such as sand and gravel or limestone. Meanwhile, hydraulic conductivity refers to the ability of the aquifer materials to transmit water, which in turn controls the rate at which groundwater will flow under a given hydraulic gradient. Both aquifer media and hydraulic conductivity of aquifer are important factor since it controls the time available for attenuation and the rate in which a contaminant will flow away from the source.

Figures 4a and 4b illustrate the aquifer media and hydraulic conductivity of Pandak and Bambanglipuro according to the geological map, boreholes data and slug test.

2.7 Soil Media (S)

Soil media refers to that uppermost portion of the vadose zone characterized by significant bi-

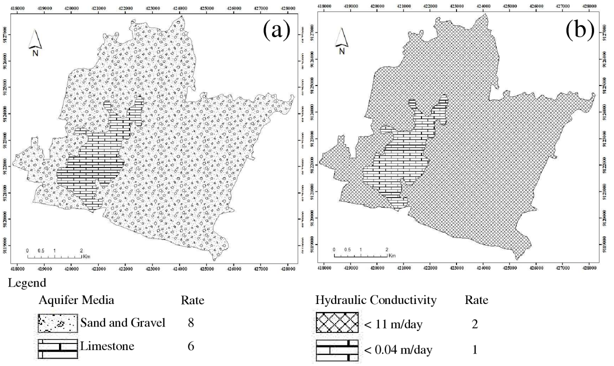

Figure 4: a) Aquifer media and b) Hydraulic conductivity of aquifer ranges and corresponding rating according to DRASTIC in the study area.

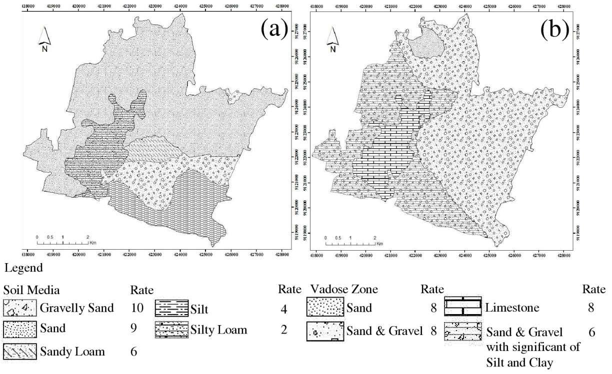

Figure 5: a) Soil media and b) vadose zone ranges and corresponding rating according to DRASTIC in the study area.

ological activity (Aller *et al.*, 1987). Soil is commonly considered the upper weathered zone of the earth which averages three feet or less. Soil has a significant impact on the amount of recharge which can infiltrate into the ground and hence on the ability of a contaminant to move vertically into the vadose zone (Figure 5a and 5b). Moreover, where the soil zone is fairly thick, the attenuation processes of filtration, biodegradation, sorption, and volatilization may be quite significant.

2.8 Impact of Vadose Zone (I)

The vadose zone is defined as that zone above the water table which is unsaturated. The type of vadose zone media determines the attenuation characteristic of the material below the typical soil horizon and above the water table (Aller *et al.*, 1987).

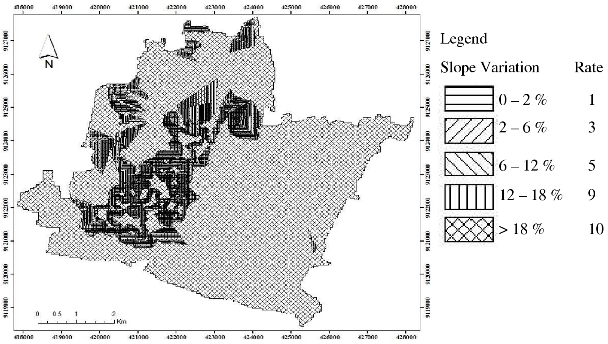

Figure 6: Slope variation ranges and corresponding rating according to DRASTIC in the study area.

2.9 Topography (T)

Topography parameter, in DRASTIC method, refers to the slope and slope variability of the land surface. Basically, topography helps control the likelihood that pollutant will run-off or remain on the surface in one area long enough to infiltrate, since the greater the chance of infiltration, the higher the pollution potential associated with the slope (Figure 6).

2.10 Application of Hoelting Method to the Study Area

Hoelting Method was developed by the Geological Survey of the individual states of the Federal Republic of Germany in 1995 (Voigt *et al.*, 2004). It is another point-count system which takes the unsaturated zone into consideration. The degree of vulnerability is expresses as the protective effectiveness (the ability of the cover above an aquifer to protect the groundwater) of the soil cover down to a depth of 1 m (the average rooting depth) and the rock cover (unsaturated zone). The higher the total number of points, the longer the approximate residence times for water percolating through the unsaturated zone and in consequence the greater the overall protective effectiveness.

Thus the overall protective effectiveness (P_T) is calculated using the following formula:

$$P_T = P_1 + P_2 + Q + HP$$

Table 1: Value of soil factor according to effective field capacity.

ΣeFC (mm) down to 1m	*Soil factors (S)*
> 250	750
> 200 – 249	500
> 140 – 199	250
> 90 – 139	125
> 50 – 89	50
≤ 50	10

Source: Hoelting et al. (1995)

Table 2: Typical effective field capacity of soil.

Soil Type	*eFC (mm/dm)*
Fine Sand	20.0 – 21.5
Medium – Coarse sand	8.0 – 11.0
Sandy loam	12.5 – 21.0
Silty sand	13.0 – 26.5
Clay	11.0 – 16.0
Silty loam	14.5 – 21.0

Source: AGBODEN (1996)

Where P_1 is the protective effectiveness of the soil cover, ($P_1 = S\,W$); S: effective field capacity (eFC) of the soil (each eFC class is assigned a different rating down to 1 m depth the average rooting depth), W: percolation factor
P_2 is the protective effectiveness of the rock cover, $P_2 = W(R_1T_1 + R_2T_2 + ... + R_nT_n)$; R: rock type where R_s (R_s = O.F) stands for consolidated rocks and R_u for unconsolidated rocks, O is a factor for rock type, and F is the degree of faulting, jointing and karstification), T: thickness of the rock cover above the aquifer.
Q is bonus points for perched aquifer systems (500 points).
HP is bonus points for hydraulic (artesian) pressure condition (1500 points

The values of each parameter are shown on the Tables 1–6 and the class for overall protective effectiveness is shown on Table 7.

Table 3: Value of sub-soil type factor of unconsolidated materials.

Type of sub-soil: unconsolidated materials	*Point of sub-soil factor*
Clay	500
Loamy Silt, Silt	250
Loamy sand, silty sand	90
Slightly clayey sand, clayey sand gravel	75
Sand	25
Gravelly sand, sandy gravel	10
Gravel, Breccia	5

Source: Hoelting et al. (1995)

Table 4: Value of rock type factor of consolidated rock (O).

Rock type	*Factor (O)*
Claystone, shale, marlstone, siltstone	20
Sandstone, quartzite, massive igneous rocks, metamorphic rock	15
Porous sandstone, porous effusive volcanic rock (e.g. tuff)	10
Conglomerate, breccias, (tuffaceous) limestone, dolomite, gypsum rock	5

Source: Hoelting et al. (1995)

Table 5: Value of factor (F) according to the degree of discontinuity.

Hydraulic features	*Factor (F)*
Non-jointed	25
Slightly jointed	4
Moderately jointed, slightly karstic	1.0
Moderately karstic	0.5
Strongly jointed, fractured or karstic	0.3
Not known	1.0

Source: Hoelting et al. (1995)

Table 6: Percolation factor (W) according to recharge rate.

U (mm/a)	*P-ET$_P$ (mm/a)*	*Factor (W)*
≤ 100	–	1.75
> 100 – 199	≤ 100	1.50
> 200 – 299	> 100 – 199	1.25
> 300 – 399	> 20 – 299	1.00
≥ 400	> 300 – 399	0.75
	≥ 400	0.50

Source: Hoelting et al. (1995)

Table 7: Class for overall protective effectiveness.

Overall protective effectiveness	*Total number of points*	*Approximate residence time in the unsaturated zone*
Very high	> 4000	>25 years
High	> 2000 – 4000	10-25 years
Moderate	> 1000 – 2000	3-10 years
Low	> 500 – 1000	Several months to 3 years
Very low	≤ 500	A few days to 1 year; in karstic rocks often less

Source: Hoelting et al. (1995)

3 Results

Results of groundwater vulnerability assessment from DRASTIC and Hoelting methods are shown in Figure 7. The diagram apparently shows that there is no relation or interaction between intrinsic groundwater vulnerability from DRASTIC model and actual contaminant concentration in the study area at all. Similar fact has been proved by some researcher that in the case of DRASTIC model, only little correspondence exists between the most vulnerable and the most contaminated . The correlation between intrinsic vulnerability from Hoelting method and actual contaminant concentration represent as a curve where average of actual nitrate concentration in groundwater ranges respectively according to the classes; Very High > High > Medium > Low > Very Low.

Since each method of determining vulnerability may reflex in different parameters and applicable at certain hydrogeology system, the only way of gaining confidence in vulnerability mapping is by comparing the results of various techniques and analyzing their consistency in practical case studies where contamination has already occurred (Striger *et al.*, 2005; Gogu *et al.*, 2003; Vias *et al.*, 2005; Ferreira and Oliveira, 2003).

Believed to be a very conservative ion in the groundwater, nitrate contaminant has been chosen as an indicator contaminant for the evaluation. In order to facilitate the evaluation of the vulnerability, a new set of maps is created by subtracting the assessed vulnerability class from the nitrate contamination class. However, for the evaluation, source of nitrate is also. The two principal anthropogenic sources of nitrate in the study area are from chemical fertilizers and domestic wastewater leakage from septic tank (or faecal coliform).

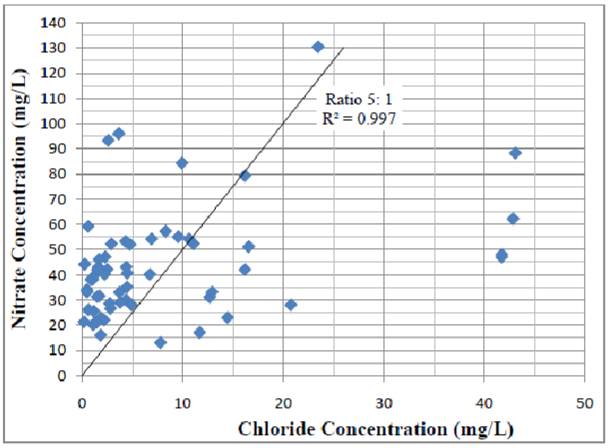

Figure 9: Nitrate vs Chloride concentration in groundwater of the research area.

From many experiments, ARGOSS (2001) has concluded that where the nitrate:chloride ratio is between 1:1 and 8:1, then it is likely that the nitrate is primarily from a faecal source. As in fact, the diagram shows that the nitrate:chloride ratio is approximately 5:1, hence the source of nitrate is originally from on-site sanitation (Figure 9).

4 Discussion and Conclusion

Producing vulnerability map of one area is a very challenge work for hydrogeologist. However, comparing vulnerability map conducted from two methods is more difficult since it will express carrying distribution pattern, which have similarities beneath strong different and even contradiction. Thus, it is recommended to all new researchers to choose a method in same system group for the comparison and assurance of the produced map, as also mentioned by Gogu *et al.* (2000), to avoid a wrong judgement. Because of the limitation of this research, some study can not be done. Hence, it is recommended to others researchers to conduct more research in this area. For instance, the specific vulnerability map of Nitrate and Chlo-

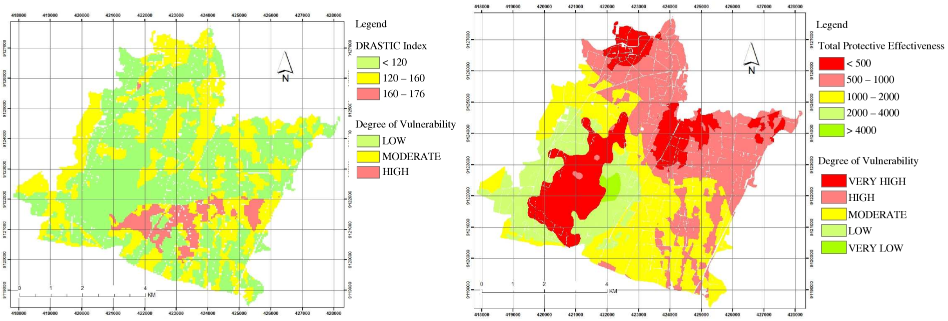

Figure 7: Map of intrinsic vulnerability of groundwater within the study area using DRASTIC and Hoelting method.

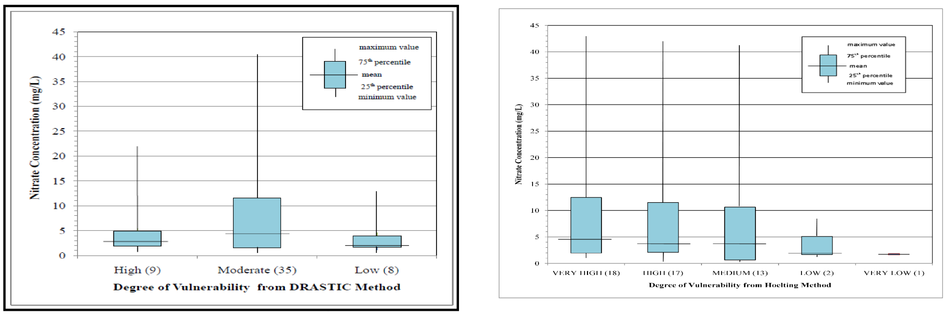

Figure 8: Boxplot diagram between groundwater nitrate concentration and a) DRASTIC; b) Hoelting Vulnerability Class.

ride should be done in order to assure the quality of groundwater for the supply. Some further study should also be done by statistical regression to assure the accuracy of the evaluation. For the environmental protection sound, it should focus not only the contaminant but also its source and other affecting factor such as on-site sanitation improvement, water use planning, and its land use management.

As mention above, protection should be more highly concerned, as the remediation is difficult and expensive, especially at the most northern part of both areas whose groundwater is very vulnerable to be polluted. Concerning to the nitrate contamination, on-site sanitation should be improved to reduce the risks, since it is the primary source of nitrate in the study area. Otherwise the groundwater will not be usable as water supply in few months time. Basically, as communities develop, there is increasing pressure for the land and thus encroachment into areas where sanitation is controlled may occur over time. Unless the community and support agencies have plans to counter-act this. In addition, risk of contamination will increase when basic protective measures are not well-maintained.

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