Groundwater vulnerability assessment in Randublatung groundwater basin using SINTACS-LU model

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Abstract. Randublatung groundwater basin is one of the crucial areas in Central Java that involves agricultural activities, which rely on groundwater sources. Agricultural activities have impacted the declining groundwater excellent of the Randublatung groundwater basin. The groundwater exploration was executed from an unconfined shallow aquifer that is in particular composed of alluvial deposits. Therefore, vulnerability evaluation to delineate regions most vulnerable to contamination from anthropogenic resources has come to be essential for sensible useful resource management and land use planning. This study estimates groundwater vulnerability by applying the SINTACS-LU model, which uses eight parameters to assess groundwater vulnerability and the geographical information system (GIS) in the Randublatung groundwater basin. The final subject level of SINTACS-LU (intrinsic vulnerability index) was created by multiplying the sum of each evaluation parameter by its specific weight. The resultant SINTACS-LU vulnerability map of the study area indicates that the areas most likely to be contaminated are between Kradenan and Keduntuban districts. Elsewhere, Rather high to high SINTACS-LU index values were observed, indicating areas of high vulnerability potential.

1. Introduction

Randublatung groundwater basin is one of the essential areas in Central Java that involves agricultural activities, which depend on groundwater resources. Agricultural activities have impacted the decline groundwater quality of the Randublatung groundwater basin. One way to utilize these resources is groundwater exploration from below the ground surface, such as dug wells or bore wells. The groundwater exploration was carried out from an unconfined shallow aquifer which is mainly composed of alluvial deposits. Therefore, vulnerability assessment to delineate areas more susceptible to contamination from anthropogenic sources has become essential for sensible resource management and land use planning.

The hydrological properties of rocks strongly influence groundwater availability to store groundwater in the inter-grain cavity media or gaps[1]. In the basin area (valley), it can form shallow groundwater zones with direct contact with the surface area, such as dug wells or bore wells. The groundwater exploration was carried out from an unconfined shallow aquifer which is mainly composed of alluvial deposits. Therefore, vulnerability assessment to delineate areas more susceptible to contamination from anthropogenic sources has become essential for sensible resource management and land use planning.

The hydrological properties of rocks strongly influence groundwater availability to store groundwater in the inter-grain cavity media or gaps[1]. In the basin area (valley), it can form shallow groundwater zones with direct contact with the surface area, so that it can be one of the driving factors for pollution if pollutants contaminate it for a long time. Pollutants can come from domestic waste or household activities, such as household waste, soap residue from washing, and sanitation waste[2].

The Randublatung Zone is a low zone consisting of Alluvium deposits composed of 2 parts, namely at the top consisting of Alluvium deposits of silt-sandy clay size, while at the bottom consisting of Alluvium deposits of sand-gravel size[3][4]. Along the northern and southern boundaries of alluvial deposits at elevations of 25 and 50 m, there is coarse sand and gravel from the core deposits[3].
Meanwhile, Alluvium deposits with the upper clay size spread over the entire area with thicknesses varying from 1-30 m[3].

Morphological conditions also affect shallow groundwater conditions. The morphology in the north and south is hilly, which tends to have a higher elevation than the central region, which is plain. The morphological condition causes shallow groundwater flow in the northern and southern areas to flow and accumulate in the central part. The type of lithology also affects the direction of shallow groundwater flow in the study area. The northern and southern regions are composed of claystone lithology, causing the water not to enter and be stored intensively into the soil. As a result, most of the water flows from a shallow groundwater table to the central region.

Hydrogeological conditions strongly influence the availability of water. Hydrogeology is the condition of groundwater availability in rock formations (regional geological conditions). Aquifer productivity consists of three conditions: high productivity in the middle, average productivity in the middle and east, and small local productivity distributed in the west and east of the area[5].

Groundwater susceptibility to pollution can be modeled using compiling information on aquifer parameters[6][7]. The soil vulnerability assessment approach developed by Foster in 1987 using the GOD method is a simple analysis based on three parameters, namely aquifer type, aquifer lithology, and aquifer depth[8]. The development of vulnerability with multi-parameter criteria triggers vulnerability by considering the condition of the surface texture of the soil with an infiltration rate as developed by Ferreira et al.[9] using the SEEPAGE method[9][2]. SINTACS was proposed and developed by Civita[10] and Civita and De Maio[11] for improving and adapting the DRASTIC model to the particularities of Italy. The letters in SINTACS are the first letters of the Italian words that define the model factors. The new factor, LU, for considering the land use effect on the groundwater vulnerability. One of the main advantages of the SINTACS-LU model is the vulnerability evaluation using several numbers of informational layers, which limits the impact of errors or unforeseen problems on the final output[12].

Therefore, this study focuses on assessing groundwater vulnerability by considering the hydrogeological and physical properties of the surface soil that affect the rate of acceleration of the entry of pollutants into the aquifer using the SINTACS-LU method. This study aims to identify the potential for groundwater pollution spatially with a hydrogeological approach in shallow groundwater aquifers and close to the surface in the Randublatung groundwater basin.

2. Material and Methodology

Randublatung groundwater basin is the area where the study was conducted, and it is located in the center of Java at the latitude 07°9'17.55" - 07°15'57.66" South and the longitude 111°11'23.39" - 111°36'26.12" East. The total area of the Randublatung groundwater basin is about 203 Km². The region's land use includes the natural forest, water bodies, paddy fields, farmlands, and residential areas. The study area is presented in figure 1.

In the methodology of assessing groundwater vulnerability of the Randublatung Groundwater Basin, the first thing to collect is the data needed as a parameter for groundwater vulnerability. After that, the SINTACS-LU method is weighted according to the management priority of the groundwater vulnerability zone. Finally, patching is carried out to obtain groundwater vulnerability zones.
Figure 1. Study area

The SINTACS method is a numerical approach using the following parameters: (S) *soggiacenza* (depth of phreatic), (I) *infiltrazione* (infiltration), (N) *non saturo* (aeration condition), (T) *tipologia della copertura* (soil texture), (A) *acquifero* (aquifer media), (C) *conducibilita* (hydraulic conductivity), (S) *superficie topografica* (topography slope)[10][11]. One of the main advantages of the SINTACS-LU model is the vulnerability evaluation using several numbers of informational layers, which limits the effect of errors or unforeseen problems on the final output. Moreover, the suggested model has the layer of land use more than the basic SINTACS one[12]

The assessment of each class and the weighting of the SINTACS-LU vulnerability parameters are presented in Table 2. The weighting is carried out on each parameter to describe the conditions in the field, as in Table 3. The eight parameters linear variables are calculated from the assessment results and weighting, resulting in a vulnerability index value. The calculation of the SINTACS-LU vulnerability index value uses the following formula[13]:

\[
VI = SrSw + IrIw + NrNw + TrTw + ArAw + CrCw + SrSw + LUrLUw
\]

where:
- \( r \) (rating): the rating of the parameter (Table 1)
- \( w \) (weight): the weight of the parameter (Table 2)

Spatial Analysis of groundwater vulnerability for pollution using the SINTACS-LU approach uses a Geographic Information System (GIS). The classification of the level of vulnerability of groundwater to pollution is obtained from the grouping of the range of vulnerability index values (Eq. 1). The criteria or range of levels of groundwater vulnerability pollution are presented in Table 4.

In limited climatologic homogenous areas (as it is the case in the present study), Rao[14] has proposed empirical relationships to determine the aquifer net recharge \( (R) \)[15]:

\[
R = 0.20(P - 400) \text{ for areas with } P \text{ between 400 and 600 mm}; 
\]

\[
R = 0.25(P - 400) \text{ for areas with } P \text{ between 600 and 1000 mm}; 
\]

\[
R = 0.35(P – 600) \text{ for areas with } P \text{ above 1000 mm}; 
\]

where \( R \) and \( P \) expressed in mm[15].

| Parameters          | Classification | Rank | Parameters   | Classification | Rank     |
|---------------------|----------------|------|--------------|----------------|----------|
| Depth of phreatic   | 0.0-2.0        | 10.0 | Soil texture | Clay           | 1.0 – 1.5|
| Parameters                  | Classification | Rank | Parameters                  | Classification | Rank |
|----------------------------|----------------|------|----------------------------|----------------|------|
| Infiltration (mm/year)      |                |      |                            |                |      |
| 0 – 50                     | 1 – 2.25       |      | 50 – 100                   | 2.25 – 4.5     |      |
| 100 – 150                  | 4.5 – 6.5      |      | 150 – 200                  | 6.5 – 8.25     |      |
| 200 – 250                  | 8.25 – 9.25    |      | 300 – 350                  | 9.25 – 8       |      |
| 350 – 400                  | 8 – 6          |      | 400 – 450                  | 6 – 4.75       |      |
| >450                       | 4.75 – 4.5     |      |                            |                |      |
| Aeration Condition         |                |      |                            |                |      |
| Coarse alluvial sediment   | 6 – 10         |      | Hydraulic conductivity    | 0.07 – 0.1     | 3    |
| Karst limestone            | 8 – 10         |      | (m/day)                    | 0.1 – 0.864    | 4    |
| Fractured limestone        | 4 – 8          |      |                            | 0.864 – 4.32   | 5    |
| Silt dolomit               | 2 – 5          |      |                            | 4.32 – 8.64    | 6    |
| Fine-moderate alluvial sediment | 3 – 6    |      |                            | 8.64 – 43.2    | 7    |
| Sand                       | 4 – 7          |      |                            | 43.2 – 86.4    | 8    |
| Sandstone, conglomerate    | 5 – 8          |      |                            | 86.4 – 366.39  | 9    |
| Turbidite sequences        | 2 – 5          |      |                            | 0 – 3          | 10   |
| Silt volcanic              | 5 – 10         |      |                            | 3 – 5          | 9    |
| Marl, claystone            | 1 – 3          |      |                            | 5 – 7          | 8    |
| Clay, silt, peat           | 1 – 2          |      |                            | 7 – 10.5       | 7    |
| Pyroclastic rock           | 2 – 5          |      |                            | 10.5 – 13.5    | 6    |
| Silt metamorphose          | 2 – 6          |      |                            | 13.5 – 16.5    | 5    |

| Parameters                  |                |      |                            |                |      |
|----------------------------|----------------|------|----------------------------|----------------|------|
| Topography slope (%)       | 16.5 – 19.5    | 4    | Land use                   | Natural / Forest | 4    |
|                            | 19.5 – 23      | 3    | Agriculture                | 6               |      |
3. Result and Discussion

3.1 Groundwater Vulnerability Parameters

3.1.1. Soggiacenza (depth of phreatic) (S)

*Soggiacenza* (depth of phreatic) (S) is a parameter with the value of the phreatic depth of the groundwater level. The depth of the water table is the distance from the ground surface to the groundwater level. This condition (distance) affects the potential for pollution if it is shallower than the groundwater level. Shallow groundwater conditions are a triggering factor for pollution. It is influenced by shallow rock thickness, which correlates with the fast seep and enters the groundwater aquifer[16]. In areas with shallow groundwater conditions, it has the advantage of obtaining groundwater. Still, it has factors that encourage groundwater vulnerability. If there is a source of pollutants on the soil surface, they can seep and fall into the aquifer system with a relatively short distance. The dynamic conditions of the depth of the groundwater table are obtained from measurements in the field.

Based on the measurement results, the depth value is obtained with a range of 0-5 m below the ground surface. However, it was found locally at a 5-10 m in the Cepu sub-district and some Kradenan sub-districts. The results of the assessment of groundwater vulnerability factors from phreatic conditions are presented in Figure 2a.

3.1.2. Infiltrazione (infiltration) (I)

*Infiltrazione* (infiltration) (I) or infiltration conditions are events where groundwater seeps horizontally, which is influenced by gravity with units of mm/hour[17]. Infiltration condition (I) is the ability to pass water in rock cavities. In terms of pollution, infiltration conditions influence the...
absorption and flow of pollutant sources into the soil to enter the aquifer. The more porous the rock is
traversed, it has the higher potential for vulnerability. Infiltration conditions in pollution susceptibility
are if the soil's ability to pass water into the soil is high, it accelerates the movement of pollutants into
the soil aquifer system. Meanwhile, suppose the soil's ability to pass water into the soil is low. In that
case, the source (supply) of water on the surface becomes large, resulting in accumulation on the soil's
surface into puddles and runoff.

The infiltration rate is obtained from the equation of soil texture measurements in the field. The
infiltration rate assessment was obtained from the correlation of surface soil texture with the equation
by Rao[14]. Based on the above equation (Eq. 2-4), the infiltration values in the study area ranged
from 250.95 to 466.90 mm/year. The condition of the infiltration rate in the study area is shown in
Figure 2b.

3.1.3. Non saturo (aeration condition) (N)

Non saturo (aeration condition) (N) aeration conditions in rock or unsaturated conditions are
aquifer parameters of the inter-grain size media. Aeration conditions are unsaturated zone conditions
in rock formations. Concerning pollution susceptibility, an aeration condition is an approach of rock
physical aquifer parameters from hydrogeological properties to an unsaturated zone. Data on aeration
zones or unsaturated zones were obtained from the distribution soil type, and then the data were
updated by using field measurements and lithology type.

The distribution of aeration zones in rock or unsaturated zones is presented in Figure 2c. Based on
these conditions, there are two (2) susceptibility assessments for the composition of coarse alluvial
sediment with a vulnerability level of 8. In contrast, the composition of fine-moderate alluvial
sediment has a lower vulnerability value of 5.

3.1.4. Tipologia della copertura (soil texture) (T)

Tipologia della copertura (soil texture) (T), or the condition of soil texture, is a vulnerability
parameter of the density properties of the constituent materials, thus affecting the spread of infiltration
of pollutant sources pollutants on the surface. Soil texture was obtained from a soil map and updated
in the field by testing soil texture.

Based on the results of observations and soil texture testing, it is known that the parent rock that
forms the soil comes from the breakdown of Kalibeng formation and Tambakromo formation.
Therefore, clay soil texture has a low level of vulnerability, which is influenced by its impervious
nature, which slows it down to resist the movement of water into the soil[18][19]. For example, in the
condition of fine sandy clay, texture has a value of 4.5 to pollution susceptibility, and coarse sandy
clay has a vulnerability level of 6. The distribution of soil texture is presented in Figure 2d.

3.1.5. Acquifero (aquifer media) (A)

Acquifero (aquifer media) (A) media (lithology) aquifers are geological formations that make
structure rocks or water-saturated rock layers below the soil surface that can and store and transmit
water[20]. The aquifer media assessment was obtained from the Ministry of Public Works[3]. In
general, the rock constituents are volcanic deposits, fine-coarse sand, and tuff. The presence of
groundwater is known to be in the composition of sand and gravel along with some silt and clay. The
greater the parameter value, the more susceptible it is to pollution. Aquifer lithology with inter-grain
media in the form of sand has factors that encourage the acceleration of pollution. Medium to coarse-
grained media between grains could drain sources of pollutants in a short time. The lithology of the
groundwater aquifers is evenly distributed in the study area, as shown in Figure 2e.

3.1.6. Conductibilita (hydraulic conductivity) (C)

Condutibility (hydraulic conductivity) (C) or hydraulic conductivity is a value that indicates the
ability of rocks to pass air in rock cavities with units of m/second[6]. The hydraulic conductivity
parameter is the condition of the rock in passing water in the cavities with units of m/second [1]. The faster the groundwater is released, the faster polluted by pollutant sources [21] [16]. It can be seen that the conductivity value or passing value (K) in the study area is 45-79 m/sec located in the middle part of the study area, while in some areas, it is 10.9 – 35.8 m/sec.

The range of groundwater passing values has a vulnerability value to attack in the three classes. The results of the assessment and weighting of the hydraulic conductivity or passing (K) groundwater values are presented in the spatial distribution is illustrated in Figure 2f.

3.1.7. Superficie topografica (topography slope) (S)

Superficie topography (topography slope) (S) The slope is a physical condition of the slope that affects the movement of groundwater on the surface [22]. The slope of the slope affects the flow of surface runoff. The flatter conditions can trigger pollution susceptibility so that the area can become a gathering place for surface runoff and become puddles. The presence of these puddles can trigger the entry of pollutant sources or pollutants into groundwater (aquifers). The sloping topography has the potential to become a place for inundation or gathering of water, and if it lasts for a long time and repeatedly, it can become a zone of entry of pollutant sources (pollutants) into the aquifer system [18]. While the slope conditions are increasingly sloping has a minor vulnerability, the gradient influences this, or the steeper slope value will drain water. There will be no puddles and no process of infiltration of surface water into the soil [6].

The slope conditions were obtained from the digital elevation model data extraction (DEM) from Geospatial Information Agency (BIG). The data used is DEMNAS with a resolution of 30 m. The digital elevation model (DEM) is converted into a slope in percent (%) with a geographic information system (GIS).

Based on the calculation, it is known that there are ten classes of the slope. The assessment of the flat slope class (0-2%) is 9.5 or has the highest vulnerability compared to the very steep-steep slope condition (> 25%) with a value of 1, the lowest value or least affecting. The results of the assessment and weighting of groundwater vulnerability parameters to pollution are presented spatially in Figure 2g.

3.1.8. Land use (LU)

Groundwater utilization will be closely related to land use that develops in an area [23] [4]. Land use in human life is an aspect that cannot be ruled out because humans use the land for different purposes to fulfill various activities and necessities of life [4]. The difference used is based on human needs, their abilities, and land-use suitability [4]. Each land use has a value and weight for its impact on groundwater vulnerability. Figure 2 (h) shows the Randublatung Groundwater Basin; in general, the land use is used as moor, shrubs, paddy fields, agricultural fields, and settlements [4].

3.2 Groundwater Vulnerability Analysis with SINTACS and SINTACS-LU.

The rank and weight of groundwater vulnerability to pollution are calculated from the index value (Eq. 1). Scenario weighting using SINTACS for normal conditions. The vulnerability index value of SINTACS has a range of 139 - 219. This class belongs to the medium vulnerability class (105-140), relatively high (140-186), high (186-210), and very high (>210)—scenario weighting using normal conditions. In comparison, the vulnerability index value of SINTACS-LU has a range of 169 - 259. This class is included in the vulnerability class relatively high (160-210), high (210-240), and very high (>240).
3.3 Groundwater Vulnerability Zone

The results of overlaying vulnerability zones with settlements show areas of densely populated conditions, including high vulnerability zones, as presented in Figure 3 and Figure 4. The vulnerability of groundwater to pollution is relatively high, having the nature of being partially or up to 50% polluted by pollutants; this can occur continuously repeatedly[24][16]. Groundwater susceptibility to high pollution requires pollution by all pollutants with high intensity, in a long period and relatively quickly. The slightly high vulnerability has the characteristics of up to 50% of pollutants, and is disposed of continuously or repeatedly[25].

**Figure 2.** The distribution zone of (a) depth of phreatic, (b) infiltration, (c) aeration condition, (d) soil texture, (e) aquifer media, (f) hydraulic conductivity, (g) topography slope, and (h) land use
Based on the SINTACS method, the groundwater vulnerability zone to moderate contamination area is 0.01%, moderately high is 70.06%, high vulnerability is 26.89%, and very high vulnerability is 3.05% of the Randublatung groundwater basin area (Figure 3). On the other hand, based on the SINTACS-LU method, the area of the groundwater vulnerability zone to contamination is relatively high at 48.98%, high vulnerability to 42.59%, and very high vulnerability to 8.43% of the total area of the Randublatung groundwater basin (Figure 4). In the SINTACS method, the area in the very high vulnerability zone is located in the part of the Kradenan sub-district. Meanwhile, in the SINTACS-LU method, areas with very high vulnerability are found in parts of Kradenan and Kedungtuban Districts. The distribution of the percentage area of the vulnerability zone is presented in Table 5.

High vulnerability zone conditions are located in the middle area of the study with physical factors such as shallow aquifer conditions and groundwater table depths ranging from 0-2.5 meters. The annual recharge in high vulnerability areas was 300-350 mm/year. Aeration conditions in high vulnerability areas are coarse alluvial sediment and soil texture fine sandy clay. The High vulnerability
area was gently sloping topography and generally land used as paddy fields. The aquifer characteristic in this area has a hydraulic conductivity value of 45-79 m/sec.

The multi-criteria research on hydrogeological properties resulted in the level of groundwater vulnerability being divided into three classes. Dominant factors affecting vulnerability include phreatic depth, aeration conditions (unsaturated zone), and land use. Assessment using the SINTACS-LU method produces index values with a relatively long range. The most dominant parameters involvulnerability can be known, namely the depth of the groundwater table and soil texture. The SINTACS-LU method can represent vulnerabilities spatially on a small scale. However, the calculation using the SINTACS-LU method requires the availability of relatively large amounts of data so that it becomes an obstacle in modeling the vulnerability of groundwater to pollution.

| Range of vulnerability | % area  |
|------------------------|---------|
| SINTACS                | SINTACS-LU |
| Moderate               | 0.01     | -         |
| Rather High            | 70.06    | 48.98     |
| High                   | 26.89    | 42.59     |
| Very High              | 3.05     | 8.43      |

4. Conclusion

The SINTACS-LU method can present vulnerability index values with an extended range of values to identify vulnerability zones in more detail. Based on the calculation results, it is known that zones with high susceptibility occur because of the interaction of surface conditions and free aquifer parameters. However, there are shortcomings in the SINTACS-LU assessment, namely the need for quite a lot of data to calculate the vulnerability value. In addition, the SINTACS-LU parameter only considers hydrogeological properties (aquifer parameters) statically and land use parameters but does not consider water recharge, which has a factor in diluting pollutants and accelerating the rate of pollution.

Suggestions that can be given are periodic monitoring of the quantity and quality of water samples based on drinking water quality standards and integrated waste management. Therefore, the sample wells for monitoring of quantity and quality of groundwater, education, and the information of waste management, especially domestic waste, making sanitation integrated with wastewater treatment plants, and for the very high vulnerability. It is necessary to make local regulations regarding integrated waste and industrial waste management.

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