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Submission date: 23-Mar-2023 06:04PM (UTC-0700)
Submission ID: 2044936808
File name: 2023-01-JWLD-25.pdf (2.24M)
Word count: 7444
Character count: 40082

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JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2023.143761
2023, No. 56 (I–III): 203–214

Determination of groundwater recharge–discharge zone to support water resources in Galur–Lendah area, Indonesia

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RECEIVED 21.05.2022 ACCEPTED 05.12.2022 AVAILABLE ONLINE 13.03.2023

Abstract: The impact of changes in regional development along with the construction of Yogyakarta International Airport in Kulon Progo Regency may affect land use changes as the activities of the surrounding population. Galur–Lendah area, which is located near the city of Yogyakarta and acts as the entrance to Kulon Progo, will also develop. Along with these developments, the determination of the groundwater recharge–discharge area is needed to ensure the availability of groundwater at this site. The purpose of this study was to determine the zonation of groundwater recharge–discharge areas to support the availability of groundwater. The method of research is a spatial analysis using a geographic information system (GIS) based on ratings and weighting values for six parameters, including slope, rainfall, groundwater table depth, soil type, rock permeability, and land use. The field hydrogeological was also conducted to find out rock permeability and groundwater quality (pH, *EC*, *TDS*). The results showed that areas with potential for groundwater recharge were in the central and northeastern parts of the study area and the discharge zones in the north and south were with potential infiltration values of 26–43 and 44–59, respectively. However, the recharge area can still function as a discharge zone.

Keywords: discharge, groundwater, recharge, spatial, zonation

INTRODUCTION

Hydrogeological research has been developed in various regions throughout Indonesia to assist communities in providing clean water. Water is a vital resource and strategic need [Undang-Undang ... 2019] and therefore, we must be able to maintain sufficient quantity and quality of water. The provision of clean water has its own challenges and this is highly dependent on the water sources (groundwater and surface water), water supply, and sanitation.

Groundwater is a water resource that is increasingly needed, shifting surface water's position for daily human life needs [PAAI, GWWG 2016]. Nowadays, surface water is sometimes polluted, so groundwater becomes a better alternative to meet the needs of life for water. Thus, the potential of groundwater needs to be studied to provide water in sufficient quantities and of good quality.

Water resources in Kulon Progo Regency have been studied by several researchers in terms of lineament and topography [Listyani *et al.* 2018; 2019]. Even, the local and intermediate shallow groundwater flow systems may also develop in the high areas of this district [Listyani *et al.* 2021]. The groundwater potential around the Progo River has been studied by Listyani and Budiadi [2018] who stated that shallow groundwater is closely related to local morphology.

One of the potential groundwater studies can be done by knowing the site's position in a groundwater basin. In addition, groundwater potential needs to be supported by understanding the recharge–discharge zone. By knowing the recharge–discharge zone, we can make efforts to better protect groundwater and maintain its sustainability.

Today, GIS technology has developed rapidly and extensively facilitates various types of research. Spatial analysis in information technology is currently developing very advanced. Various discoveries have been achieved by developing this technology, among others, based on GIS and remote sensing technology. Lahay and Koem [2022] made a spatiotemporal map of changes in inundation in Lake Limboto. The spatiotemporal

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information about changes in inundation area in the lake can be generated quickly based on Landsat images and GIS. On the other hand, the main factors in the erosion potential method including soil erodibility, soil protection, slope, temperature, and rainfall were also evaluated using GIS [Zeghmar *et al.* 2022]. GIS will provide a more integrated picture of groundwater potential because it combines several parameters quickly and accurately. Then one of the efforts to find out the infiltration–discharge zone can also be done using this technology.

Spatial analysis carried out by GIS is expected to help achieve recharge–discharge zoning in the region, namely Galur and Temon districts, Kulon Progo Regency, Yogyakarta Province, Java, Indonesia. This region is growing quite rapidly, along with the development of the western part of Yogyakarta due to the construction of a new airport (Yogyakarta International Airport). The Galur and Temon districts become accessible for residents and tourists who pass through Yogyakarta to the airport or cities west of Yogyakarta. This area belongs to the eastern part of Kulon Progo Regency. Because it is close to the city of Yogyakarta, it is predicted that these districts will experience rapid development. With the rapid growth of the region, the need for groundwater is increasing.

This study aims to determine the groundwater recharge–discharge zone, especially shallow groundwater using GIS technology. Shallow groundwater is potentially closely related to land use on the surface [Li *et al.* 2017]. Human activity is an important factor that contributes to water deterioration and then encourages water pollution. Massive exploitation of urban supplies and irrigation can affect the salinisation of waters [Aouidane *et al.* 2022]. If pollution occurs in the catchment area, then in the discharge zone there will also be a potential decrease in groundwater quality [Azimov *et al.* 2022], and even increased activity puts pressure on groundwater quality [Rubiantoro *et al.* 2022]. Moges and Dinka [2022] said that in order to identify and describe areas far from pollution, various groundwater assessment techniques have been developed worldwide. Identification of vulnerabilities also should be started with understanding the function of the site as a recharge or discharge zone. Lakhdari *et al.* [2022] clearly stated that knowledge of the quality and quantity of groundwater is a prerequisite for encouraging investment in the development sector of a region. To support this, synthesis and analysis of the chemical quality of water in the recharge area have also been carried out. Therefore, the GIS method will help comprehensively evaluate several hydrological–hydrogeological parameters to be used for more accurate discharge–charge zoning.

MATERIALS AND METHODS

GEOLOGICAL CONDITION OF LOCATION AREA

According to Van Bemmelen [1949], the physiography of Central Java is divided into seven sections stretching from north to south. Based on this zoning division, the research area is included in the Dome in the Central Depression zone (known as Solo zone) with specific locations in the districts of Galur and Lendah, Kulon Progo Regency, Yogyakarta Special Province, Indonesia (Fig. 1). It is limited by coordinates 110°10'00"–110°16'15" E and 7°53'00"–7°58'45" N. Most of this region is located in the physiography of

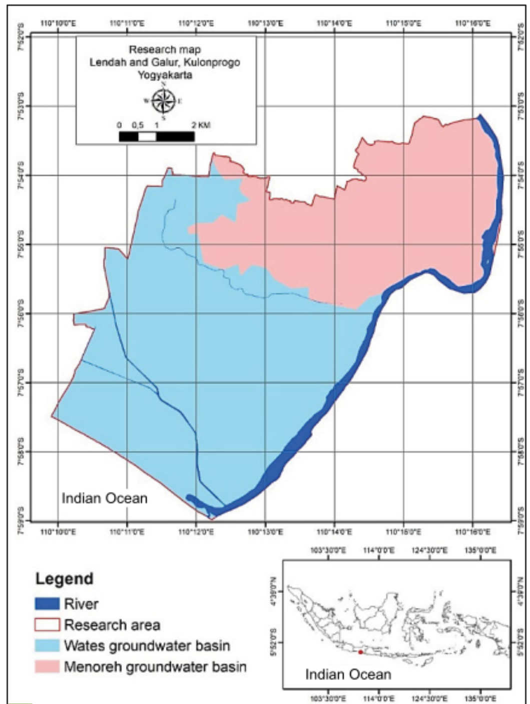

Fig. 1. Map of the location index of the research area; source: own study

the Solo zone, which consists of coastal deposits, including sand, silt, and clay [Rahardjo *et al.* 1995]. A small part of the study area is compact rock from the Sentolo formation and the Old Andesite formation, where outcrops can be found in the northern and northeastern parts of the Lendah District.

The centre of the research area is the alluvial plain. This morphology spreads lengthwise in the west–east direction. The lithology that composes this plain is alluvial deposits consisting of ranges from clay to gravel, which are produced by fluvio-volcanic processes [Santosa 2010]. The dominant flow pattern is dendritic, indicating uniform rock resistance and non-dominant structure [Srijono *et al.* 2011]. The southern part of Galur District forms a coastal plain morphology, spread along the southern coast. The rocks that make up this region are coastal alluvial deposits (fluvio-marine). As in the alluvial plain morphology, the drainage pattern in this site also develops dendritic.

The northern part of the study area is part of the West Progo Hills. The geology of this area has been discussed by several experts using paleontological, facies, petrological and stratigraphic analysis approaches. The experts who have carried out the research include Van Bemmelen [1949], Rahardjo *et al.* [1995], and Budiadi [2008]. The previous study shows that the regional stratigraphy of West Progo from old to young is composed of Nanggulan formation, Tua Andesite formation, Jonggrangan formation, Sentolo formation, and alluvial deposits.

McDonald and Partners [1984] further divided the alluvial deposits in the West Progo Hills into the Wates formation and the Yogyakarta formation. The Wates formation is composed of loose material resulting from fluvial activity, including from the Progo River. This formation is spread south and southwest of the

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West Progo Hills to the south coast [Yogyakarta Pwhemro – CV. CPK 2016]. The Yogyakarta formation is composed of loose material resulting from volcanic activity, including the Old and Young Merapi formations. The spread of this formation covers the eastern and southern parts of the West Progo Hills.

The rock outcrops that can be found in the study area according to regional geological maps are alluvial (Qa), Young Merapi volcanic deposits (Qmi), and Sentolo formation (Tmps) [Rahardjo *et al.* 1995]. Alluvial deposits are found in gravel, sand, silt, and clay along the Progo River and coastal plains. The Young Merapi deposit comprises tuff, ash, breccia, agglomerates, and inseparable lava flows. The Sentolo formation consists of limestone and marl sandstone.

According to the regional hydrogeological map [Effendi 1985] that has been clipped as in Figure 2, our research area has two hydrogeological units.

1. Extensive, moderately productive aquifers. This aquifer has low to medium continuity; groundwater level varies from near ground level to >5 m, and well discharge is generally <5 $dm^3 \cdot s^{-1}$. The rocks that make up this aquifer are alluvial deposits of rivers and beaches. River alluvial deposits are clay, silt, and sand with medium to high graduation. Coastal sediment aquifers consist mainly of loose sand of medium-high permeability.
2. Poorly productive aquifers to local importance. This aquifer has very low continuity and is local. Groundwater can be obtained in valley areas or weathering zones in limited quantities. This aquifer is generally composed of the Sentolo formation. This unit is generally supported by layered limestone (calcarenite), marl, and tuff, with low to moderate permeability, which causes the groundwater potential to be local.

The research area is also included in the western part of the Wates Groundwater Basin [Geological Agency 2011]. This basin is a coastal aquifer system [Yogyakarta Pwhemro – CV. CPK 2016]. The aquifer system in this basin can be divided into two subsystems (Photo 1), including the dune and the alluvial-coastal. The dune subsystem is composed of a sand dune aquifer. The alluvial-coastal subsystem is composed of the Wates and Sentolo formation aquifers, both of which have poor aquifer quality. The Wates formation is a multilayer aquifer with a thickness of 20–30 m, while the aquifer of the Sentolo formation is supported by jointed limestone with a thickness of about 950 m.

STUDY MATERIALS

The tools required in this research are field geology and hydrogeology tools. Field geological tools include hammers, compasses, cameras, and GPS. Field hydrogeological tools involve measuring equipment for rock permeability in the field (bucket, pipe, and stopwatch) and measuring groundwater quality (pH meter, TDS meter, and EC meter). The research material required in the field is a regional geological map of scale 1:100,000, a regional hydrogeological map of scale 1:250,000, and a topographic map of scale 1:25,000. The samples taken were water from

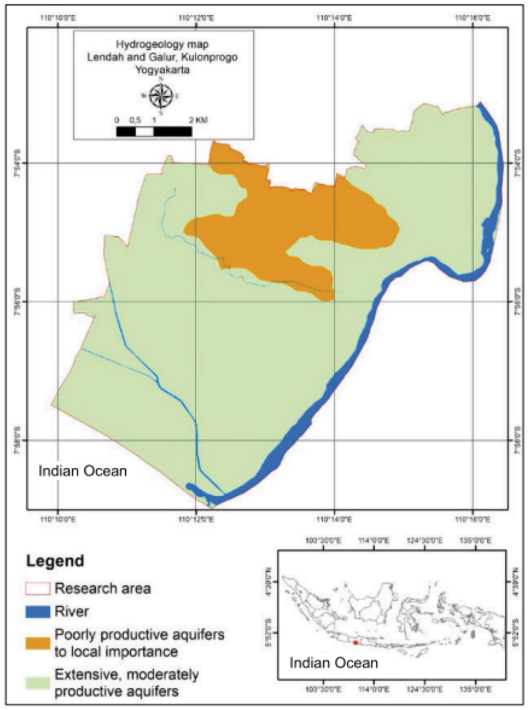

Fig. 2. Clipping of regional hydrogeological map for Lendah and Galur; source: own elaboration based on Effendi [1985]

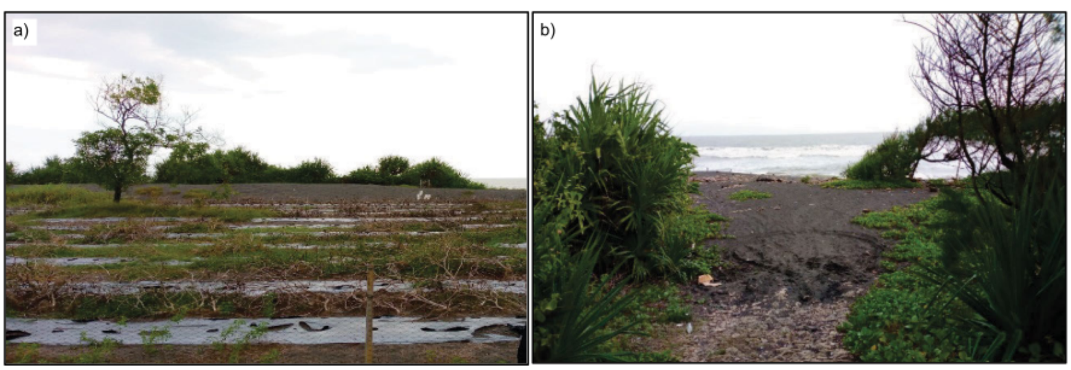

Photo 1. Landscape appearance of Trisik beach, Galur, Kulon Progo Regency area: a) alluvial–coastal subsystem; b) sand dune subsystem (phot.: *R.A.T. Listyani*)

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several dug wells and rocks. In addition, some secondary data, which includes information on rainfall, soil types, and land use from the relevant agencies, are collected to support the analysis.

STUDY METHODS

Data collection

The field survey begins with observing the following geological and hydrogeological conditions.

a) geological mapping to determine the stratigraphy and petrology of rock characteristics that have the aquifer potential; this mapping is complemented by taking rock samples for petrological description in the laboratory;
b) groundwater surface mapping and its quality by measuring groundwater quality in dug wells equipped with water sampling;
c) measurement of rock permeability (hydraulic conductivity) in the field.

The following data is obtained from the field and the secondary data analysed:

1) slope (morphology) is obtained from the Shuttle Radar Topography Mission (SRTM) map and the results of field checks;
2) rock permeability (*K*) is measured in the field and partially interpreted based on the similarity of sediment characteristics;
3) rainfall–precipitation (*P*) is the secondary data obtained from three rainfall stations from BMKG [2020];
4) land use system is the secondary data originating from BPSKKP [2021];
5) soil cover is obtained from BBSDLP [2018];
6) shallow groundwater table measured directly from dug wells in the field; measurement of the physical-chemical properties of groundwater in the field is carried out to determine the pH, *EC*, and *TDS*, accompanied by groundwater sampling for laboratory testing; the results of laboratory chemistry tests on the content of major ions are used to determine the hydrochemical facies.

Data analysis

Spatial determination of recharge–discharge zones is carried out using a GIS overlay system and weighting (Tab. 1) to determine the potential of each region (scoring). From Table 1, the

Table 1. The weighting of several parameters determines the recharge–discharge zone in Galur and Lendah

Parameter	Rank	Class	Rating	Weight
Hydraulic conductivity (m·d^{-1})	very high	>1,000	5	6
	high	(10–1,000]	4	
	moderate	(0.01–10]	3	
	low	(0.0001–0.01]	2	
	very low	≤0.0001	1	
Rainfall (mm·y^{-1})	very high	>4,000	5	5
	high	(3,000–4,000]	4	
	moderate	(2,000–3,000]	3	
	low	(1,000–2,000]	2	
	very low	≤1,000	1	
Land use	very high	forest	5	4
	high	garden	4	
	moderate	shrubs	3	
	low	empty land, vacant land	2	
	very low	settlement, swamp, ricefield	1	
Soil type	very high	Regosol	5	3
	high	alluvial	4	
	moderate	lithosol	3	
	low	latosol	2	
	very low	grumusol	1	
Slope	very high	>40°	5	2
	high	(20°–40°]	4	
	moderate	(10°–20°]	3	
	low	(5°–10°]	2	
	very low	≤5°	1	
Groundwater depth (m)	very high	>10	5	1
	high	(7.5–10]	4	
	moderate	(5–7.5]	3	
	low	(2.5–5]	2	
	very low	≤2.5	1	

Source: own elaboration based on DANARYANTO *et al.* [2007].

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modification was made from permeability to hydraulic conductivity to simplify aquifer conditions. Using the Spatial Analyst Tools menu in the ArcGIS application, mapping the recharge–discharge area can be made. The results of this analysis are in the form of a map of the recharge–discharge zone based on scoring that refers to the water infiltration value (Tab. 2).

Table 2. Water infiltration value of potential zone in this study

No.	Water infiltration value	Potential zone
1	26–43	discharge
2	44–59	recharge

Source: own study.

In Table 2, the results of physical-chemical tests of groundwater from the laboratory were used to verify the outcomes of GIS processing. Groundwater quality data in the form of temperature, pH, *TDS*, and *EC* were obtained. Together with the hydrochemical facies data, it was used for the data verification step. The result of hydrochemical characterisation will support the recharge–discharge zone determination. The groundwater quality in the recharge area will usually be different from the quality in the discharge zone. Therefore, the quality of this groundwater can be compared or assessed for its suitability with the obtained recharge–discharge zone.

The calculation of the recharge value based on DANARYANTO *et al.* [2007] is as follows.

$$Recharge\ value = (K_w \cdot K_r) + (R_w \cdot R_r) + (L_w \cdot L_r) + \\ +(T_w \cdot T_r) + (S_w \cdot S_r) + (G_w \cdot G_r) \quad (1)$$

where: K = hydraulic conductivity, R = rainfall, L = land use, T = type of soil, S = slope; G = groundwater depth; w = weight value; r = rating value.

RESULTS

SLOPE (MORPHOLOGY)

The results of field observations can be divided into four following geomorphological units (Photo 2):

1) structural undulating to rolling morphology (S3) – this landscape occupies 5% of the total study area and has a gentle, rather steep slope, which ranges from 8 to 17°; the region has undergone weathering, and there are indications of geological structures that control the morphological formations;
2) structural rolling morphology (S9) – this morphology occupies 20% of the study area, with a slope of about 15°; this site has also experienced weathering, and there are indications of geological structures that control morphological formations;
3) fluvial plain (F4) – this landscape is the most widely distributed (about 65%) and has a slope of 0–2°, formed from erosional and sedimentation processes influenced by fluvial activity;
4) eolian plain (A5) – this morphology has a slope of 0° or almost 0°, with a spread of 10%, formed by wind activity that transports material.

The research area does not differ from this gentle slope to flat relief. Regions that are slightly high and slightly steep are in the north, while from the middle to the south are generally very gentle (Fig. 3).

HYDRAULIC CONDUCTIVITY (*K*)

The research site is dominated by alluvial deposits, which are widespread, both as fluvio-volcanic and coastal deposits. In addition to alluvial deposits, Tertiary rock outcrops as bedrock underlying alluvial deposits are also found in several places. The exposed Tertiary rocks are part of the Sentolo formation (Photo 3). This rock is generally in the form of clastic limestone, yellowish-white when fresh to blackish when weathered, with

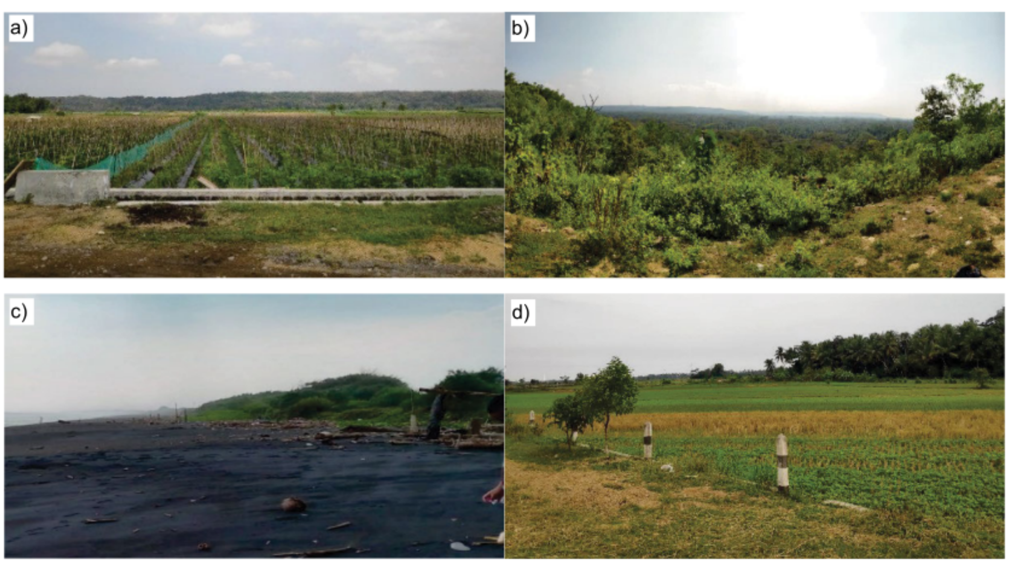

Photo 2. Examples of landscape features and morphological units: a) S3, b) S9, c) A5, d) F4 (phot.: *R.A.T. Listyani*)

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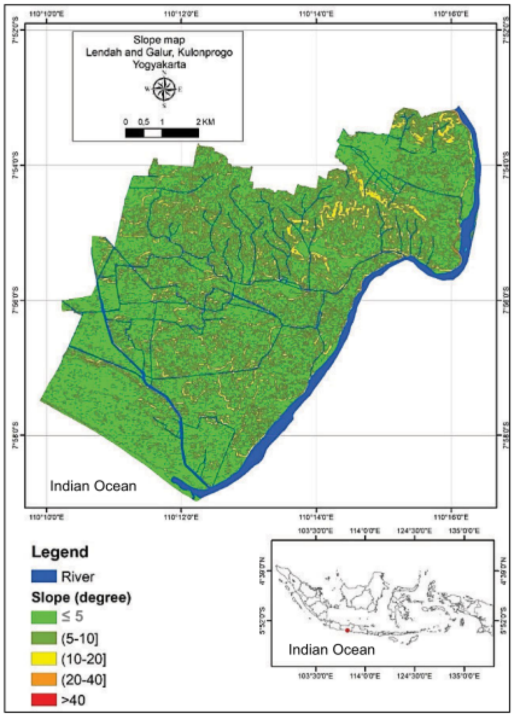

Fig. 3. Map of the slope of the Galur and Lendah; source: own study

Photo 3. Sentolo formation as the bedrock of alluvial deposit: a) limestone outcrop, b) calcilutite-calcarenite intercalation (phot.: *R.A.T. Listyani*)

a thin massive layered structure, sometimes showing a slump structure.

Hydraulic conductivity usually reflects the rock's permeability. Infiltration tests were carried out in three locations covered with alluvial deposits. The hydraulic conductivity test results in the field showed a value of 7.56–45.01 $m \cdot d^{-1}$. From these tests, the hydraulic conductivity value of the rock tested is under the hydraulic conductivity value of medium-coarse sand [TODD 1980]. Table 3 shows the representative hydraulic conductivity calculated based on MORRIS and JOHNSON [1967]. Meanwhile, the hydraulic conductivity value of bedrock (Tertiary) and sediments in other sites is approached by interpreting the hydraulic conductivity value of the regional geological map. The results are shown in the hydraulic conductivity map in Figure 4.

Table 3. Representative hydraulic conductivity values

Material	Hydraulic conductivity ($m \cdot d^{-1}$)
Fine sand	2.5
Medium sand	12
Coarse sand	45
Limestone	0.04

Source: own elaboration based on MORRIS and JOHNSON [1967].

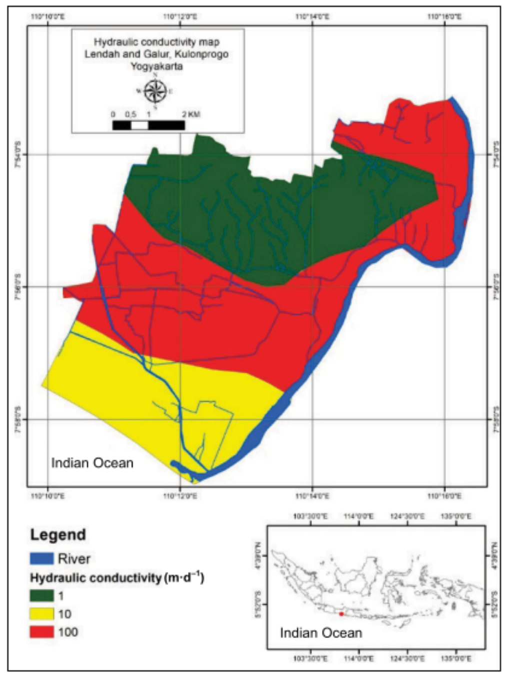

Fig. 4. Map of rock permeability of Galur and Lendah; source: own study

RAINFALL/PRECIPITATION (*P*)

Rainfall varies in some locations and affects the groundwater potential. Usually, the water resources of a groundwater basin will be expected to be affected by climate change [HEYI *et al.* 2022]. In this study, groundwater is also strongly supported by rainfall, especially in the rainy season.

Average rainfall data was obtained from the Sleman Meteorology Climatology and Geophysics Council (Ind.: Badan Meteorologi, Klimatologi dan Geofisika – BMKG) Climatology Station for Lendah and Galur [BMKG 2020]. The average rainfall in this area ranges from 196 to 206 mm per month (data for 5 years) and tends to be higher in the central and eastern parts. These rainfall data processing results are presented in the form of a rainfall map (Fig. 5).

LAND USE

Land use is also essential to consider in assessing groundwater potential. Improper management of land use will reduce the potential for groundwater in the recharge and discharge zones.

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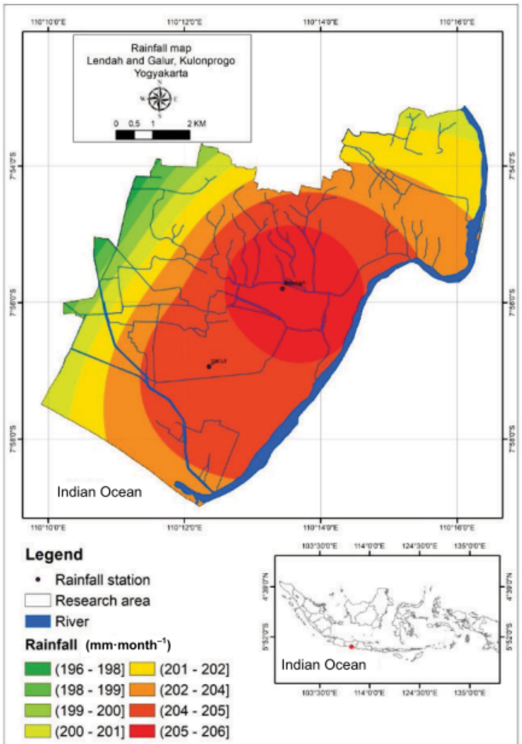

Fig. 5. Rainfall map for Galur and Lendah; source: own study

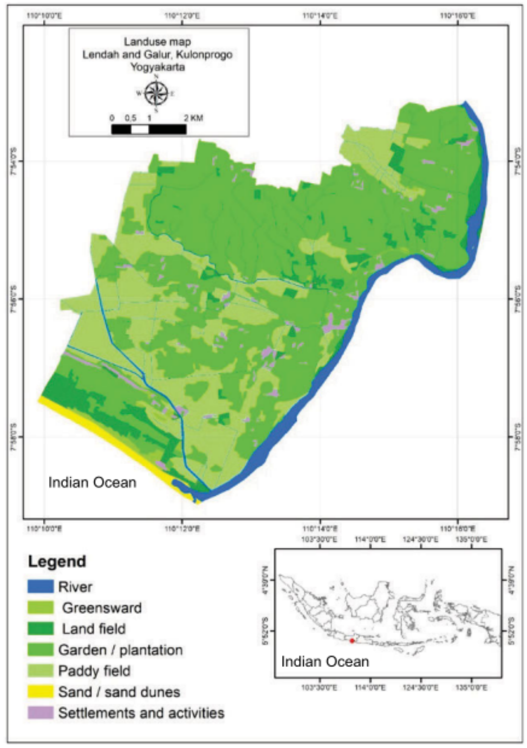

Fig. 6. Land use map of Galur and Lendah; source: own study

Groundwater should be monitored due to land use and soil balance to ensure the region's sustainable development [BENYOUSSEF *et al.* 2022].

Most of the research area is plantation land or rice fields, and only a few have been developed into residential locations (Fig. 6). This condition strongly supports the potential of the study site as a shallow groundwater recharge zone.

SOIL COVER

Soil cover has a significant influence in determining the recharge–discharge zone because the type of soil affects the ability of the soil to infiltrate rainwater. Changes in the physical properties of the soil can affect its infiltration capacity. For example, soil compaction changes physical properties [VISTRO *et al.* 2022]. Therefore, the physical properties of the soil cover are an essential consideration in the weighting of this study. BBSDLP [2018] said that several types of soil in this study were lithosols, gleic alluvial, eutric Cambisol, gleic Cambisol, eutric gleisol, eutric Regosol, haplic Mollisol (Fig. 7). The information about the types of soil can be seen in Table 4.

SHALLOW GROUNDWATER TABLE

The position of the shallow groundwater table in Galur and Lendah is shown in Figure 8. The surface of the groundwater is the position of shallow groundwater as measured from 20 resident-dug wells. In terms of depth, the position of the shallow ground-

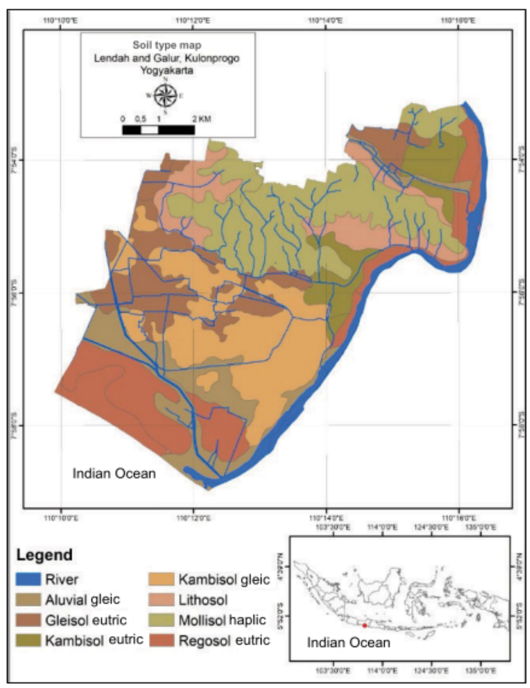

Fig. 7. Map of soil cover of Galur and Lendah; source: own study

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Table 4. Soil types and kinds in the Galur–Lendah refer to the national soil classification

Mineral soil	Horizon	Type of soil	Type characteristic	Kind of soil	Kind characteristic
Without development	AR	lithosol	very shallow soil (<25 cm) over solid rock	rocky soil	exist as colluvial at a lower slope in Lendah
	AC	alluvial	the soil is formed from young sedimentary material (alluvium); it has a characteristic horizon of A, finer texture than clayey sand	alluvial gleic	gray color, thickness of 20–100 cm, spread in southern part of Galur
	AC	Regosol	coarse-textured soil (sand, clayey sand) has an A horizon thickness >25 cm	eutric Regosol	found at coastal eolian sand at the southern end of Galur
With development	ABwC	kambisol	it has a cambic B horizon without or with A horizon, with hydromorphic indications to a depth of 50 cm from the surface	eutric Cambisol	result from weathering of limestone/sandstone of Sentolo Fm.
				Cambisol gleic	a mixture of weathered Sentolo limestone and Merapi sediment
	ABgC	gleisol	it has hydromorphic characteristics to a depth of 50 cm from the surface; have a A horizon and B horizon	gleisol eutric	weathered of fluvio-volcanic product
	ABwC	Mollisol	it has a molecular A characteristic horizon	haplic Mollisol	spread at the north end of Lendah, usually comes from weathered limestone/marl

Explanations: A = upper horizon, B = lower horizon, C = parent material, R = source rock, g = glei, dark grey, w = weathered.
Source: own elaboration based on Subardja *et al.* [2014].

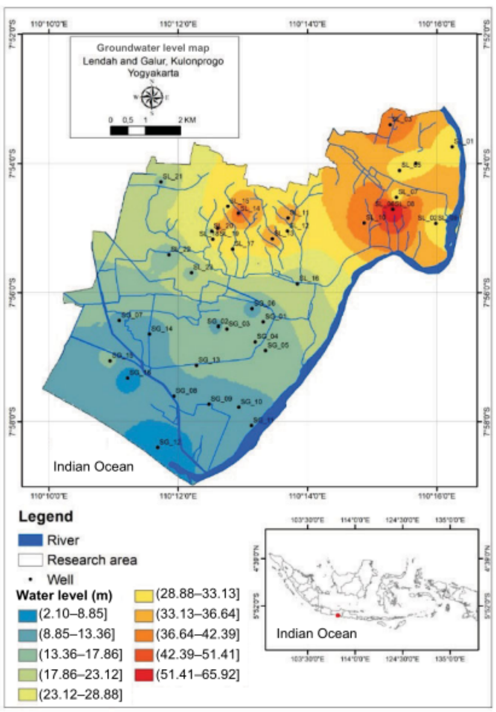

Fig. 8. Shallow groundwater table map of the Galur and Lendah; source: own study

water table ranges from 1 to 19 m from the local soil surface. When measured from sea level, the lowest groundwater level is found in Sidorejo Village, Banaran, Galur, with a 2.1 m a.s.l., while the highest position is at an elevation of 73.65 m a.s.l. in Tubin Village, Sidorejo, Lendah. The shallow groundwater flow patterns generally develop from north to south.

Wells located in the recharge zone usually have a deep groundwater table, with the groundwater flow direction vertically downwards component [Yogyakarta Pwhemro – CV. CPK 2016], beside the horizontal flow dominating. All dug wells show relatively shallow groundwater depths. The groundwater table depth in the field is measured from 0 (at springs) to 19 m in dug wells. Thus, if viewed from the groundwater level, the Galuh and Lendah have more potential as discharge zone.

Groundwater flow patterns are generally to the south, with a radial pattern anomaly developing in the northern–northeastern hills. Thus, the upper part of the hills can function as a recharge zone, while the surrounding plains to the south coast tend to act as discharge zones.

DISCUSSION

MORPHOLOGICAL APPROACH TO RECHARGE–DISCHARGE ZONE DETERMINATION

Break of slope area

The break of the slope is generally the boundary between recharge and discharge zones. The site is usually located on the morphological boundaries of plains and hills [Yogyakarta Pwhemro – CV. CPK 2016]. In the Galur-Lendah, the break of the slope is situated on the border of the S3–F4 and S9–F4 geomorphological units. The regions in the S3 and S9 units have the recharge areas potential. Thus, the areas that have the potential as recharge areas are in the northern and northeastern parts of the Lendah District. Meanwhile, the entire Galur subdistrict has the potential as a discharge zone.

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Drainage pattern

The recharge area usually has relatively short and straight tributaries, while the discharge zone usually has the main river or long tributaries [Yogyakarta Pwhemro – CV. CPK 2016]. Some of the tributaries in Lendah are tributaries of the West Progo, which are relatively short and straight, while the West Progo downstream is the main river in the Galur area. With this category, the morphologically undulating part of the Lendah area can function as a recharge area, while the plains in Lendah and the entire Galur area are discharge zones.

Table 5. Types of groundwater basin boundaries that develop in the Galur and Lendah

Boundary type			Explanation
configuration	code	category	
Horizontal	H_2	groundwater divide	it occurs in the northern part of the study area, separating the Wates GB from the sub-basin in the north and south of the hills of the Lendah area
	H_3	external head-controlled boundary	limiting Wates GB with the South Sea
	H_4	inflow boundary	it is the boundary between the Kulon Progo Dome and Wates GB
	H_5	outflow boundary	it is the boundary of Wates GB on the east side with the Progo river flow
Vertical	V_1	free-surface boundary	this boundary is located throughout the research region with shallow groundwater
	V_2	internal head-controlled boundary	occurred in the flow of the Progo tributaries
	V_3	internal zero flow boundary	it separates the alluvial-coastal subsystem from non-aquifer rocks (Sentolo formation)

Explanations: GB = groundwater basin.
Source: own elaboration based on Boonstra and Ridder [1981].

The presence of springs

Springs arise due to intersections in the hydraulic surface elevation of the aquifer with the ground surface [Kresic, Stevanovic 2009]. The region above the spring is generally a recharge zone. Only one spring is found in Lendah, namely the Jurug spring. The Jurug spring appears in a moderately sloping area, with subtle morphological differences. The appearance of this spring is supported by the presence of rock fractures in the area.

DETERMINATION OF RECHARGE–DISCHARGE ZONES BASED ON SPATIAL ANALYSIS

The research area is included in the Wates Groundwater Basin (GB) with the following hydrostratigraphy that composes this basin [Yogyakarta Pwhemro – CV. CPK 2016].

1. Alluvial–coastal subsystem (aquifer group 1, free aquifer, multilayer aquifer). This subsystem is a free aquifer, consisting of alternating semipermeable and permeable layers that are interconnected with the following materials:
   - debris of the Sentolo formation (clay, sand, and limestone) and Old Andesite formation (clay, silt, tuffaceous sand, and sandstone).
   - the Yogyakarta formation, which is a young Merapi fluvio-volcanic deposit (fine sand – conglomerate).
2. Sand dune subsystem (aquifer group 2, free aquifer). This subsystem comprises eolian deposits on the coast, consisting of fine-coarse sand material, forming a groundwater pocket system [McDonald & Partners 1984].
3. Base of aquifer (non-aquifer group). The bottom of the aquifer is rock from the Sentolo formation, where some outcrops can still be found in the northern part of the study site.

The Wates GB has several basin and subbasin hydraulic boundaries. The Wates GB horizontal boundary in Galur and Lendah refers to Minister of Energy and Mineral Resources No. 13/2009 [Peraturan … 2009] can be classified into several types (Tab. 5, Fig. 9). The cross section in Figure 9 is made from the line in Figure 10.

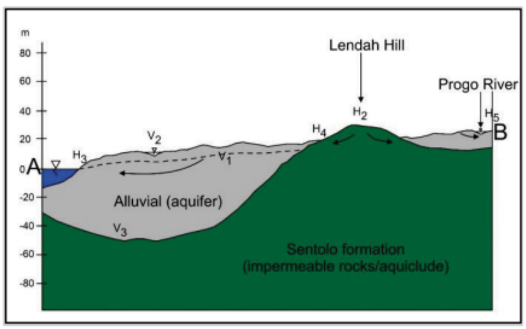

Fig. 9. Basin boundary type of the Wates GB in Galur and Lendah; H2, H3, H4, H5, V1, V2, V3 as in Tab. 5; source: own elaboration based on the model by Boonstra and Ridder [1981]

In general, the recharge zonation can be determined based on the break of the slopes; the spring's appearance; the position–density of the groundwater table; and the relationship between the groundwater table and surface water. From this basis, it can be interpreted that the shallow groundwater zone in Galur and Lendah can be divided into zones.

1. The recharge zone includes:
   - the northeastern part of the Lendah area on a rolling (hills) morphology;
   - the plains in Lendah and Galur are evidenced by the relatively young groundwater and carbonate facies.

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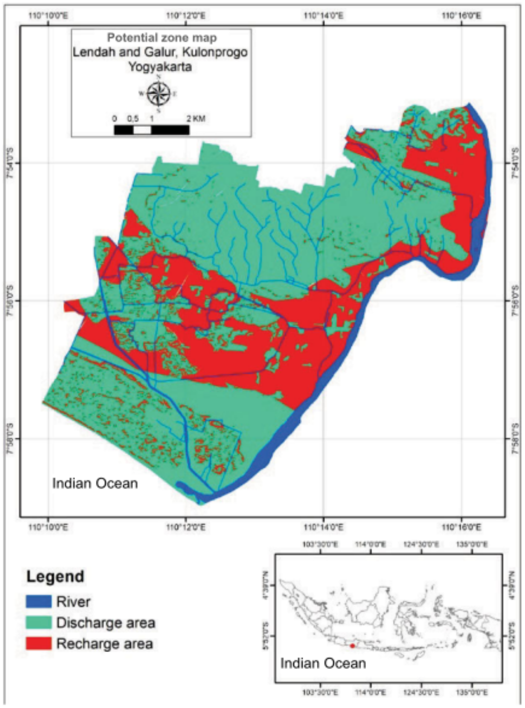

Fig. 10. Recharge–discharge zonation map of the Galur and Lendah; source: own study

2. The discharge zone covers almost all regions except the highlands at north Lendah (hills).

Thus, the entire sites in Galur District can function as recharge and discharge zones for shallow groundwater. This is supported by land functions that are still good and the type of land cover that is also potential. Meanwhile, part of the Lendah District can function as a recharge zone and most of it as a discharge area.

To delineate the recharge–discharge zone, a study was conducted on six parameters: slope (morphology), rock permeability, soil cover, land use, rainfall, and shallow groundwater level. Furthermore, the six parameters will be overlaid to determine the shallow groundwater recharge–discharge zonation. A recharge–discharge map is finally obtained from the weighting results, as shown in Figure 10 above. The northeast and middle regions have the recharge areas potential, while the north and south areas have the potential as discharge zones.

The results of groundwater facies analysis as a verification of this study indicate that all shallow groundwater is of bicarbonate type (Tab. 6). This shallow groundwater shows a relatively normal pH, low *EC*, and *TDS*. This characteristic indicates that groundwater is young and usually occurs in the recharge zone. It shows that the plains in the north and south of the study site can also function as a recharge zone. As the recharge area, especially in the centre of the region, it needs to be maintained as a recharge zone among others by maintaining the green open spaces.

Table 6. Summary of hydrochemistry of shallow groundwater in Galur and Lendah

Source	Ground water facies	pH	*EC* (μS·cm^{-1})	*TDS* (ppm)
W1	Ca-HCO_3	7.8	280	136
W2	Ca-HCO_3	7.1	370	185
W3	Ca-HCO3	7.9	670	331
W4	Ca,Mg-HCO_3	7.3	428	214
W5	Ca,Mg-HCO_3	7.4	434	218
S1	Ca-HCO_3	7.1	724	362
W6	Ca,Mg-HCO_3	7.3	312	150
W7	Ca,Mg-HCO_3	7.4	672	340
W8	Ca,Na,Mg-HCO_3	7.5	350	181
W9	Mg-HCO_3	7.8	280	136

Explanations: W = dug well, S = spring, *EC* = electrical conductivity, *TDS* = total dissolved solids.
Source: own study.

CONCLUSIONS

Determination of the recharge–discharge zone in the Galur–Lendah area through GIS has been carried out by taking into account the morphology (slope), hydraulic conductivity, rainfall, land use, soil cover, and groundwater depth. The slope is dominated by relatively flat to undulating slopes (<10°). The average rainfall in this area ranges from 196 to 206 mm per month and tends to be higher in the central and eastern parts. Meanwhile, land use in this research is agricultural land, mainly plantation land and a small amount of it is used for settlement. It strongly supports the potential of the research area as a recharge zone where the permeability variable measured by hydraulic conductivity value in the field is 7.56–45.01 m·d^{-1}. The soil types that developed were lithosol, gleic alluvial, eutric Cambisol, gleic Cambisol, eutric gleisol, eutric Regosol, and haplic Mollisol. In addition, most of the land cover also supports the potential of the recharge zone.

Referring to Boonstra and De Ridder's [1981] classification, this study area has lateral hydrogeological boundaries as H_2–H_5 and vertical as V_1–V_3. Based on the various parameters investigated, the northeastern and central parts can be identified as recharge areas. In contrast, the northern and southern regions have the potential as discharge areas. However, considering that the chemical type of groundwater in the plains shows carbonate facies that characterise young groundwater, the alluvial plains can also act as a recharge area. The centre of the study area needs to be maintained as a recharge zone among others by maintaining the existence of green open spaces.

ACKNOWLEDGEMENTS

This research was supported by the Lembaga Penelitian, Pengabdian Masyarakat dan Inovasi (LPPMI), Institut Teknologi Nasional Yogyakarta under fundamental internal research grant

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with contract No.: 16/ITNY/LPPMI/Pen.Int./PD/V/2021. The author expresses her/his gratitude to the Institut Teknologi Nasional Yogyakarta, which has provided funds for implementing the 2021 Basic Research. To all field assistants (Bella, Vilman, Basith, and Thareq) and all those who helped with the research and publication, the author appreciates and thanks a lot.

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