# GIS-based Spatial Modelling of Shallow Groundwater Quality: an Evaluation in High Populated Area of Sukoharjo, Indonesia

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***Abstract*—The development of a region can be characterised by the increasing population, regional facilities, and infrastructure. Kartasura District is one of the areas in Sukoharjo, Indonesia, that has experienced very rapid development. This negatively impacts the quantity and quality of its shallow groundwater. Water quality evaluation is needed since most of the community still uses groundwater for hygiene activities, sanitation, and drinking water. This study aimed to model shallow groundwater quality in Kartasura spatially. Field surveys and laboratory analysis were conducted across 12 villages in the study area. A comprehensive quality assessment was then carried out using nine parameters of the water quality index (WQI). Water quality modelling was performed utilising tools from the Geographic Information System (GIS) platform. Our results showed that poor class dominated the shallow groundwater quality in the study area. Specifically, poor water quality was found in the land uses of settlements and rice fields. Meanwhile, a moderate water quality index was found in the settlements and mixed gardens. These findings suggest that improvement in shallow water management is required, particularly in the region where settlements are close to industrial areas.**

***Keywords*—spatial modelling, quality, WQI, shallow groundwater, GIS**

## I. INTRODUCTION

A clean water crisis is one of the classic problems faced by people living in urban areas. It is caused by various factors, including (a) population growth, (b) urban economic growth which fails to incorporate water conservation, and (c) over-exploitation of water [1]. High population growth and development can lead to pollution and the contamination of clean water sources in urban areas, especially groundwater sources [2]. As such, groundwater contamination becomes a common issue in industrial areas, offices, agricultural areas, and settlements [3]. High population density potentially has environmental impacts when the development of infrastructure is lacking [4, 5]. Environmental sanitation activities are expected to minimise pollution, but in reality, there is a risk that in the absence of the proper infrastructure, waste is disposed to the environment directly [6].

The process of groundwater pollution begins with the entry of pollutant sources that are discharged directly into the soil and seep through the pores to the aquifer layer [7]. These pollutants will quickly seep into the aquifer layer during the rainy season. The rate of infiltration is influenced by biophysical factors on land, such as land use [8], slope [9], [10], and soil type [11]. Contaminated groundwater will be distributed according to the direction of the groundwater flow so it can contaminate residents' wells. The presence of *Escherichia coli (E.coli)* has been knows as an indication of polluted groundwater [12]. These bacteria belong to the faecal coliform group, which inhabits the digestive tract of humans and warm-blooded animals. They are opportunistic pathogens in humans and can cause diarrhoea.

A clean water crisis is also predicted to occur in Kartasura District. It is one of the urban areas of the Sukoharjo Regency, which has been experiencing rapid regional development within the past ten years. This development can be observed in the increase in (a) population (25%), (b) settlements (17%), (c) economic facilities (18%), (d) educational facilities (23%), and (e) health facilities (31%) (Fig. 1) [13]. Consequently, the increasing number of people, accompanied by increased development activities in the social, economic, and cultural fields, can impact the quality of both surface water and groundwater.

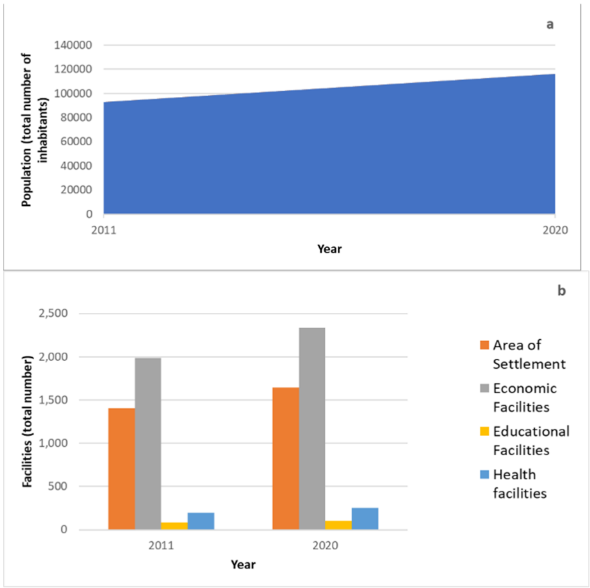

Fig. 1. Number of population trends (a). Total number of economic, educational, and health facilities (b).

As shown, this rapid regional development may increase domestic waste volume and further result in a decrease in groundwater quality. Various approaches have been conducted to assess the environmental parameters' quality using laboratory-based data [14, 15] and in combination with spatial data [16, 17]. Environmental quality assessment with spatial data is needed to indicate both the quality of the environment and its location.

While many studies have been conducted for water quality evaluation, such as in Iran, Italy, Greece, and China [18], research on the spatial modelling of shallow groundwater quality remains scarce. Previous studies focused on surface water, such as the sub-watershed water quality modelling with the ArcSWAT (ArcGIS extension for Soil and Water Assessment Tool) based on the analytic hierarchy process (AHP) [19], pollution identification using geographically weighted multivariate regression [20], and water quality dynamics modelling of a lake with a hydrodynamic approach [21]. Modelling of shallow groundwater is essential in urban areas where human activities are very intensive, whereas access to sanitation infrastructure is often lacking [22]. In this context, Geographic Information Systems (GIS) has been widely used for hydrological modelling in urban areas [23]. GIS provides tools to integrate spatial with non-spatial data, allowing the user to manage and process data more comprehensively. In addition, the water quality index (WQI) technique has been known to be operationally helpful in combining individual water quality parameters. As such benefits, it has been applied to evaluate groundwater quality, such as in the Morocco aquifer region [24] and Bangladesh [25].

This study aims to model the shallow groundwater quality of urban areas in Kartasura, Sukoharjo. We analyse the nine parameters of water in 12 sampling regions. Water quality assessment is measured by the WQI approach, and features in the GIS platform facilitate the quality modelling. Shallow water quality assessment provides crucial information for proper water management strategies in highly anthropogenic activities of urban areas.

## II. STUDY AREA

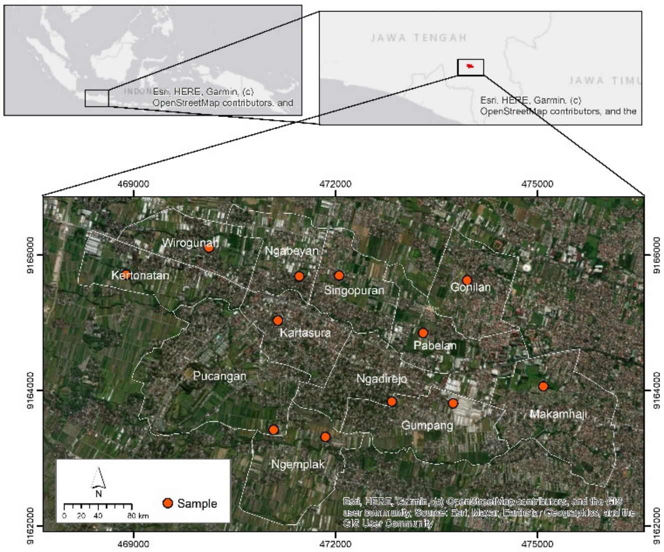

Fig. 2. Administration map of Kartasura in Sukoharjo, Central Java, Indonesia, showing the distribution of samples over the study area.

Kartasura is one of the districts of Sukoharjo Regency, Java Island, Indonesia. It is located at 110° 42'-110° 57' East Longitude and 7° 32'-7° 49' South Latitude (Fig. 2). The region covers 2,081 ha and is 121 m above sea level, with flat and sloped relief of 0–2%. There are 102 days of rain per year, with an average rainfall of 25 mm/hour. In 2020, the population density in Kartasura was reported to be 5,577 people/km$^2$. The geology of Kartasura is classified as young volcanic, consisting of rock breccia, lava, tuff, and andesite lava to basalt and alluvial deposits. Land use generally includes settlements, industry and trade, offices, mixed gardens, empty land, and irrigated rice fields [26].

## III. DATA AND METHODS

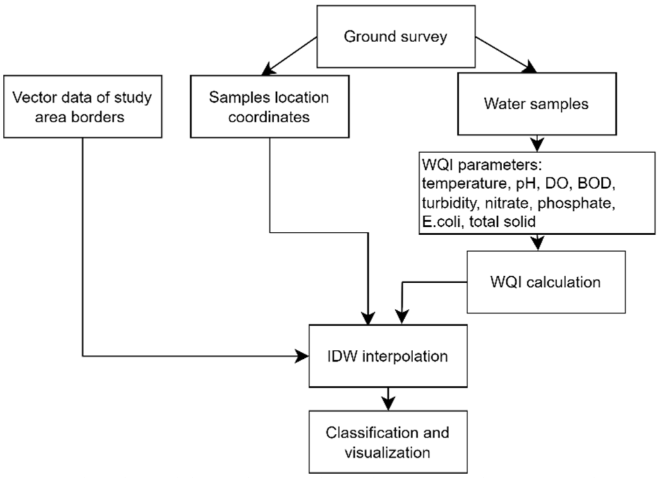

Fig. 3. Flowchart of the study to evaluate the water quality in groundwater.

Water samples were taken randomly from the 12 wells' settlements of all villages in the study area. Each sample is a ten-litre volume. We tested water quality parameters: temperature, turbidity, total solids (TS), potential of hydrogen (pH), dissolved oxygen (DO), biochemical oxygen demand (BOD), nitrate, phosphate, and *E.coli* bacteria level. The pH was measured in situ using a pH meter. DO was measured in the laboratory using a DO meter, BOD by total organic carbon analyser, turbidity by turbidimeter, and the chemical parameters by v-visible spectrophotometer. For analysis purposes, we also obtained secondary data, including population density, land use, and socioeconomic status. Fig. 3 generally presents all the steps taken for this study.

Water quality was assessed based on the National Sanitation Foundation Water Quality Index (NSF-WQI) or Water Quality Index (WQI). It is one of the instruments widely adopted to assess the level of water quality for lakes [27], rivers [17, 28], and dam reservoirs [29, 30]. WQI value was calculated using the following formula (Eq. 1):

$$NSF-WQI=\sum_{i=0}^{n} Wi\times Li \qquad (1)$$

where:

$n$ = number of water quality parameters

$Wi$ = the quality

The weight value of each parameter ($Wi$) was assigned using Table 1 [30], and the classification score of NSF-WQI was based on Table 2 [27, 30]. parameter weight

$Li$ = the value of the sub-index curve

All measured parameters were entered into the GIS platform to map the water quality. The feature of IDW

(Inverse distance weighted) in GIS was used to interpolate WQI values across the study area spatially. It is a widely used geostatistical technique to estimate values in the surrounding regions directly based on known sample measurements. This method has also been applied to predict water quality distribution [31, 32]. Finally, the water quality index was classified and visualised using the following criteria (Table 2).

Table 1. Parameter weight value (*Wi*)

| Parameter | Weight |
|---|---|
| Dissolved Oxygen | 0.17 |
| Fecal Coliform Density | 0.15 |
| pH | 0.12 |
| BODs | 0.10 |
| Nitrates | 0.10 |
| Total Phosphates | 0.10 |
| t °c from Equilibrium | 0.10 |
| Turbidity | 0.08 |
| Total Solids | 0.08 |

Table 2. Classification of the Water Quality Index (WQI) Score

| Value Range | Class |
|---|---|
| 00-25 | Very poor |
| 26-50 | Poor |
| 51-70 | Medium |
| 71-90 | Good |
| 91-100 | Very Good |

## IV. RESULTS AND DISCUSSION

### *A. Shallow Groundwater Quality Test*

Laboratory tests were used to measure the shallow groundwater quality in Kartasura. The results of the laboratory tests, based on nine parameters, are shown in Table 3, and the value distribution is presented in Fig. 4. Table 3 shows that the temperature in the study area ranged from 24.2-24.9°C. The highest temperature was in Singopuran, and the lowest was in Pabelan Village.

Table 3. Shallow groundwater quality test

| Point | Temperature (°C) | pH | DO (mg/L) | Turbidity (NTU) | BOD (mg/L) | Nitrate (mg/L) | Phosphate (mg/L) | *E.coli* (MPN/ 100ml) | TS (mg/L) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 24.3 | 7.4 | 7.18 | 4.44 | 4.22 | 0.16 | 0.19 | 34 | 668 |
| 2 | 24.2 | 7.5 | 7.54 | 2.31 | 4.72 | 26.95 | 0.55 | 140 | 608 |
| 3 | 24.9 | 7.6 | 7.11 | 1.03 | 4.43 | 7.77 | 0.23 | 170 | 520 |
| 4 | 24.7 | 7.9 | 7.9 | 3.43 | 5.51 | 2.49 | 1.08 | 33 | 368 |
| 5 | 24.5 | 7.3 | 4.14 | 19.5 | 38.11 | 0.45 | 0.07 | 220 | 540 |
| 6 | 24.8 | 7.9 | 7.79 | 11.1 | 5.08 | 2.63 | 0.49 | 920 | 220 |
| 7 | 24.4 | 6.7 | 7.3 | 3.85 | 6.23 | 5.92 | 0.65 | 170 | 495 |
| 8 | 24.4 | 7.7 | 7.67 | 4.3 | 4.8 | 5.19 | 0.52 | 240 | 316 |
| 9 | 24.6 | 7.8 | 6.83 | 3.2 | 4.46 | 1.41 | 0.13 | 7.8 | 320 |
| 10 | 24.3 | 7.8 | 7.37 | 0.84 | 5.13 | 0.25 | 0.14 | 220 | 348 |
| 11 | 24.7 | 7.2 | 6.83 | 20.4 | 3.93 | 7.03 | 1.33 | 4.5 | 468 |
| 12 | 24.8 | 6.4 | 7.06 | 8.73 | 4.18 | 1.97 | 0.92 | 70 | 378 |
| mean | 24.55 | 7.4 | 7.06 | 6.93 | 7.57 | 5.19 | 0.45 | 185.78 | 437.42 |
| limit | 20–25 | 6.5–8.5 | 9 | 25 | 2 | 10 | 0.20 | 0 | 1000 |

Note: sample points: 1. Makam Haji, 2. Pabelan, 3. Singopuran, 4. Ngemplak, 5. Kertonatan, 6. Ngadirejo, 7. Pucangan, 8. Kartasura, 9. Wirogunan, 10. Ngabeyan, 11. Gumpang, 12. Gonilan.

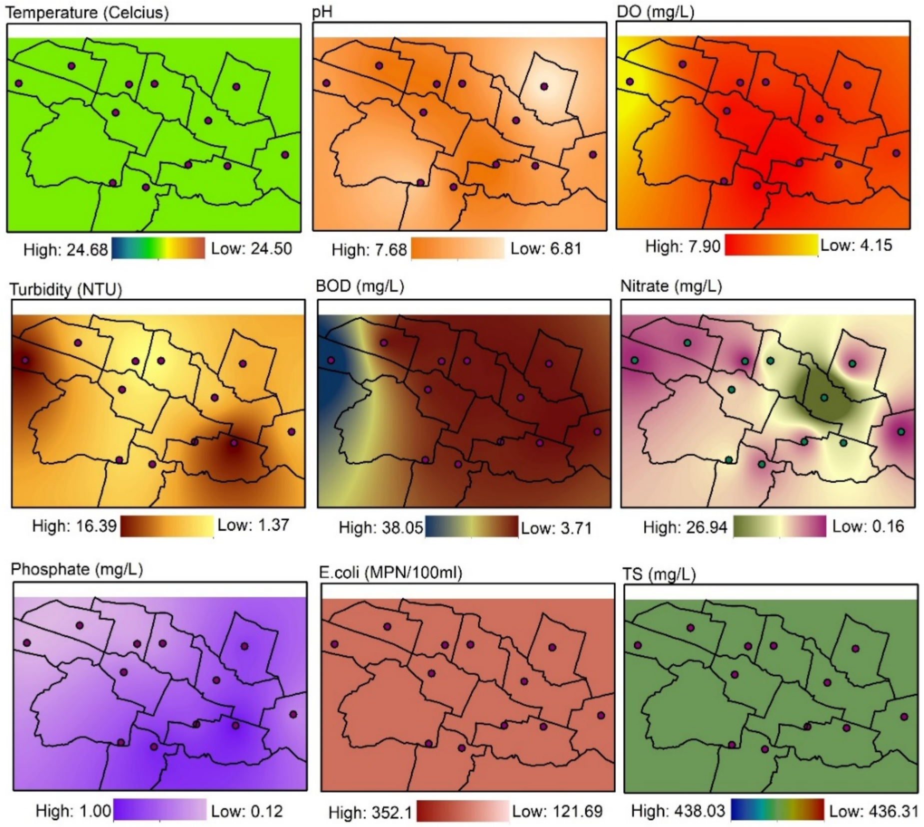

Fig. 4. Nine parameter values distribution of Water Quality Index (WQI) in Kartasura.

The pH value ranged from 6.35 to 7.92, with the highest pH value in Ngemplak and the lowest in Gonilan. The DO value ranged from 4.14 to 7.90 mg/L. The highest DO value was found in Ngemplak, while the lowest was in Kertonatan. The turbidity values ranged from 0.84 NTU (Ngabeyan) to 19.50 NTU (Kertonatan).

According to Fig. 4, the temperature in Kartasura was relatively constant over the whole area, which was between 24.2 and 24.9°C. According to Regulation No. 32/2017 issued by the Indonesian Minister of Health regarding environmental health quality standards [33]. The maximum water temperature is 20–25°C. This means that the temperature in the study area was still within quality standards for hygienic sanitation and that the groundwater was suitable for domestic use.

The average pH level of clean water quality standards for hygienic sanitation is 6.5 to 8.5. The pH value in the study area ranged from 6.35 to 7.92, so most of the groundwater had a normal pH and was suitable for hygienic sanitation purposes. Only Gonilan village had a pH value below the quality standard (Fig. 4), with a pH value of 6.35, and was classified as acidic. Hence, the groundwater in this area was unsuitable for hygienic sanitation.

The maximum quality standard for turbidity is 25 NTU. All of the villages in Kartasura had turbidity values within the water quality standards for hygienic sanitation, so they were feasible to use. Two villages, Gumpang (20.4 NTU) and Kertonatan Village (19.5 NTU) had turbidity values close to the maximum limit in the western and eastern parts of Kartasura.

The DO parameter is the amount of oxygen dissolved in water. The higher the DO value in the water, the better the water will be. At a temperature of 20ºC, the maximum DO level is nine ppm or mg/L. According to our analysis, most of the water in the study area had a dissolved oxygen content of 6–7 mg/L, which was suitable for hygienic sanitation. Only Kertonatan Village, located in the eastern region, had a low DO of 4.14 mg/L.

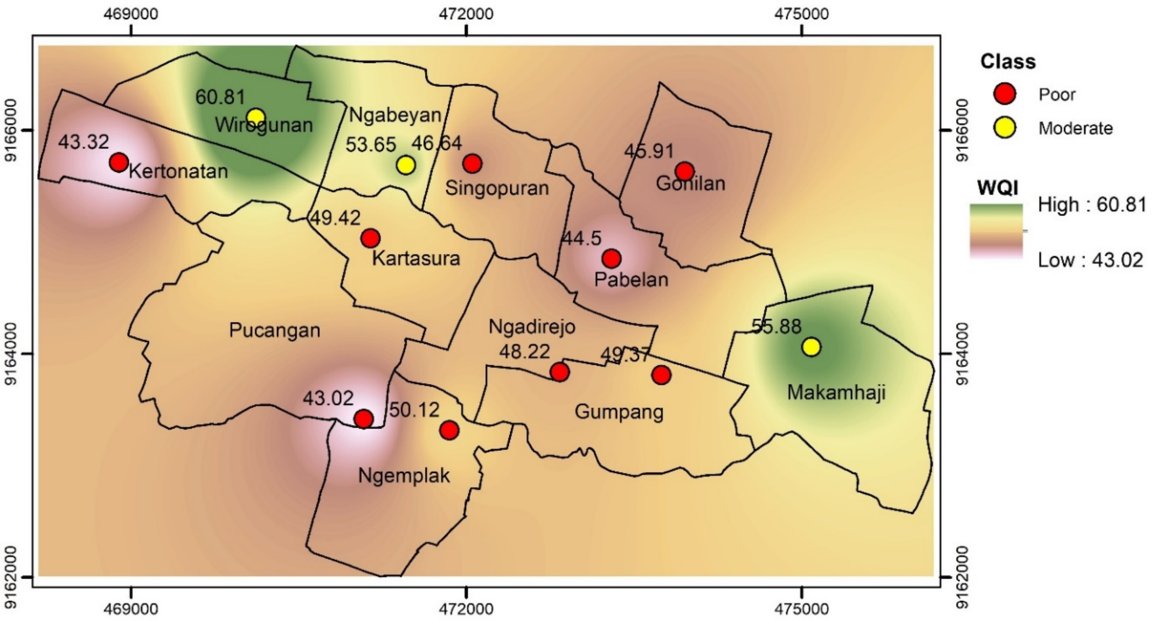

Fig. 5. Water Quality Index (WQI) distribution in Kartasura, showing two classes of water quality: poor and moderate classes.

The BOD content in groundwater in Kartasura District ranged from 4.18-38.11 mg/L. Given that class 1, the BOD threshold is set at two mg/L, the groundwater in the study area was unsuitable for use for hygienic sanitation. The highest BOD content was found in Kertonatan, at 38.11 mg/L, and the lowest was in Gumpang, at 3.93 mg/L. The number of microorganisms in the water influences the high BOD content. This is also relevant to our finding of DO distribution since the higher the BOD content, the smaller the DO contained in the water [34, 35].

In regards to the nitrate content, our examination of the groundwater samples showed that most of the samples had values below the predetermined threshold. According to Indonesian Minister of Health regulation No.32/2017 [33]. The quality standard for nitrate levels in hygienic sanitation is 10 mg/L. In Pabelan, the highest nitrate concentration was measured at 26.9 mg/L, while in all other regions, the nitrate values were below the threshold (see it in Fig. 4). In contrast, the other 11 samples indicated that the groundwater was safe for hygienic sanitation. High levels of nitrate in drinking water (above ten mg/L) can lead to health risks due to nitrate poisoning [36].

The phosphate content in the sample water showed levels ranging from 0.1347 to 1.078 mg/L. Given that the threshold value of phosphate for drinking water is 0.20 mg/L, four of the 12 water samples tested had phosphate levels below the established quality standards: Makam Haji (0.1917 mg/L), Kertonatan (0.0735 mg/L), Wirogunan (0.1347 mg/L), and Ngabeyan (0.1376 mg/L). In contrast, the highest phosphate content is in Gumpang, which is located in the western part of Kartasura and has a phosphate level of 1,328 mg/L. For the bacteria contamination, *E. coli* bacteria in groundwater samples failed to meet the requirements because the average *E. coli* content was 4.5-920 ml while the allowed standard is 0/100 ml.

### B. *Assessment of Water Quality Index (WQI)*

Based on nine explained parameters, the water quality index (WQI) can be assessed. Fig. 5 shows the distribution of WQI values in the study area. The higher the WQI value indicates, the better the water quality. As shown, there were two types of shallow groundwater quality index in Kartasura: moderate and poor. Areas that have a moderate index were clustered in the northern (Wirogunan and Ngabeyan) and eastern of the region (Makam Haji). On the other hand, those with poor indices were spread across most of the region. Areas with low WQI were located in the middle of the region, with the worst WQI observed in Ngemplak.

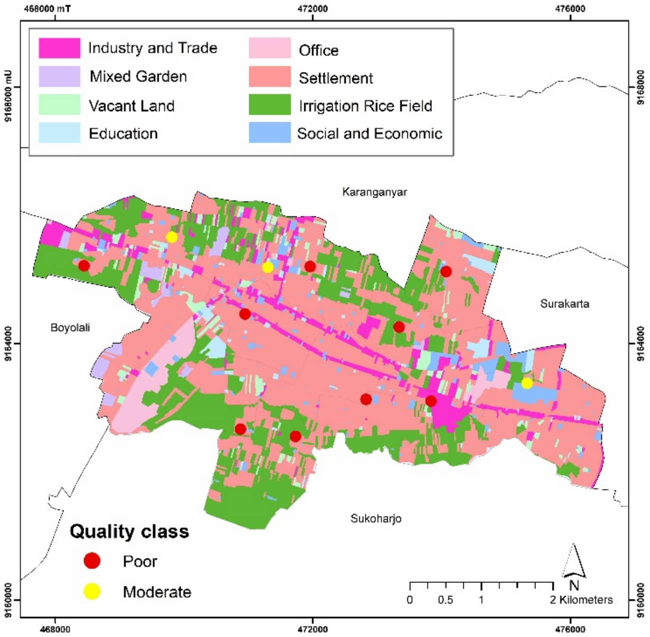

Fig. 6. Land use and Water Quality Index (WQI) distribution.

Several factors can be explained regarding the distribution of WQI in the study area. Land use may correlate with the low values of WQI. Fig. 6 provides information on the land use distribution and the corresponding WQI in that area. As shown, the majority of the WQI class in the study area was poor, indicating that the groundwater quality is improper for hygienic sanitation purposes. Poor classes were observed in the regions where a high proportion of settlements and rice fields are located (Fig. 7). Anthropogenic activity plays a role in groundwater degradation, and it potentially impacts health risks [37].

Looking into details, the highest turbidity in the groundwater was found in Gumpang Village (Table 3). Similarly, the highest phosphate content was also obtained in this village. This condition is likely associated with the location of industrial (textile) and trade activities (Fig. 6). The sampling location is about ten meters from industrial activities, indicated by the area's most significant phosphate contributor. In the industrial world, the use of phosphate itself serves to prevent hardness in steam boilers [35]. Agricultural chemical fertilisers or detergents from household waste can also influence high and low phosphate levels [36].

A high concentration of nitrate was found in Pabelan (Fig. 4). This condition can be explained by the fact that the sample was taken close to the rice fields (Fig. 6). Nitrate contamination of groundwater can be caused by the condition of wells that are too close to agricultural areas. As reported by prior studies, agricultural activities, such as plantations and rice fields, as well as the accumulation of domestic waste that seeps into the ground, are possible causes of groundwater pollution [36, 38]. This is also supported by a study [39] which mentioned that nitrate is a major contaminant in groundwater from agricultural areas.

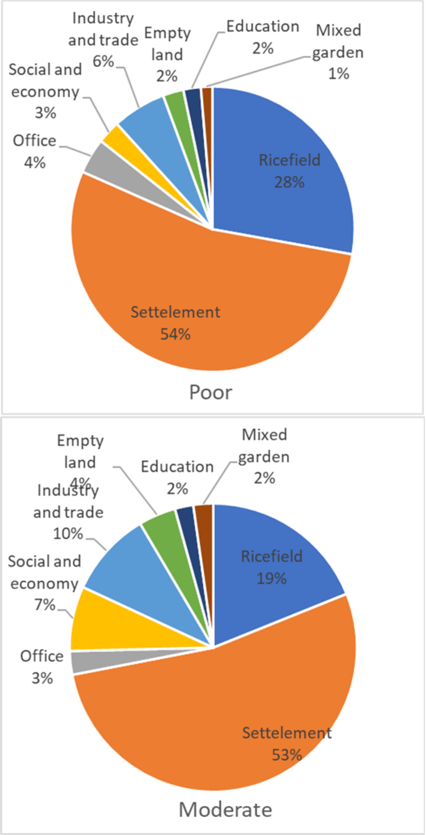

Fig. 7. Proportion of different land uses in the poor and moderate classes of WQI.

The observed low WQI could be attributed to the high density of the population represented by the large settlement areas of the region (Fig. 6). One parameter related to settlement is bacteria contamination. High levels of contamination by *E. coli* bacteria can be due to the location of the well, which is open and adjacent to a poultry coop, causing a lot of poultry manure to enter the well. This condition was found in Ngadirejo Village, where there were 920 ml of *E. coli* bacteria (the highest value in our study area). This can also be caused by a septic tank being too close to the well. As the minimum distance between the well and the septic tank should be 11 meters, the presence of wells too close to a restroom can increase the potential for groundwater contamination by *E. coli* bacteria [40]. Additionally, solid waste from settlement areas can also be a source of low water quality. Especially in developing countries, municipal solid waste dumpsite is the leading cause of pollution in groundwater [41].

As presented, the GIS map based on IDW interpolation provided information on predicting how water quality is spatially distributed in the study area. This prediction, however, should be regarded as knowing the trend or pattern rather than extracting the exact value since interpolation accuracy is determined by the number of samples. As a result, more samples are needed in the future for more accurate water quality interpolation.

## V. CONCLUSION

In this study, an assessment of shallow groundwater quality was conducted using the water quality index (WQI), which covers nine parameters of water quality. The WQI was modelled in a GIS environment. The average WQI value in the study area was 49.24, identified as poor class. Specifically, we found that most of the regions were classified as poor. Only three villages in the northern and eastern parts of the region were of moderate quality. It was also observed that the low WQI was in areas with high settlements and close to areas for rice cultivation. Therefore, there is a need for better shallow groundwater management considering the location of those land uses. As presented, modelling of shallow groundwater with GIS features can help identify the high and low quality for the target of priority interventions. This would also be beneficial in detecting areas that pose a high risk of pollutants.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## AUTHOR CONTRIBUTIONS

ANA conceptualised and designed the study, conducted the research, analysed the data, and wrote the paper. DNS conducted the research, analysed the data, and wrote the paper. NMS and RR wrote the paper. VNF wrote and reviewed the paper. All authors have approved the final version.

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