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Spatial and Seasonal Assessment of Nutrients and *E. coli* Contamination in Coastal Domestic Wells of Tanah Laut Regency

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ABSTRACT

Coastal groundwater is an essential domestic water source for communities in Tanah Laut Regency, South Kalimantan, but it is increasingly vulnerable to nutrient enrichment and fecal contamination from agricultural and domestic activities. This study assessed the spatial distribution of fertilizer-derived groundwater pollution in coastal wells and its relevance to achieving SDG 6 on clean water. Groundwater samples were collected from 50 domestic wells in five coastal sub-districts: Kurau, Takisung, Panyipatan, Jorong, and Kintap during wet and dry seasons. Ammonia, nitrate, phosphate, and *E. coli* were analyzed and classified into five water quality classes, while geographic information system-based interpolation and overlay analysis were used to identify pollution-prone zones. The results show that nitrate and phosphate concentrations were higher in wells located closer to agricultural land, with phosphate showing the strongest inverse relationship in both seasons. Phosphate increased during the wet season, while nitrate tended to accumulate during the dry season. *E. coli* contamination was associated with dense settlements and inadequate sanitation near wells. These findings indicate that coastal groundwater degradation is driven by combined agricultural, sanitation, and seasonal hydrological factors. Spatially targeted nutrient management, sanitation improvement, and wellhead protection are therefore essential to safeguard clean water access in coastal communities.

1. INTRODUCTION

Groundwater is an essential source of domestic water in many coastal communities, particularly where access to centralized piped water is limited, and households rely on shallow wells for daily needs [1, 2]. Ensuring safe groundwater is directly linked to the achievement of Sustainable Development Goal 6, which emphasizes universal access to safe drinking water, improved sanitation, and reduced water pollution [1]. However, shallow coastal aquifers are highly vulnerable because they are often unconfined, close to the land surface, affected by seawater intrusion, and exposed to pollutant inputs from settlements, sanitation systems, agriculture, and other coastal land-use activities [3-5].

Groundwater quality in coastal areas is influenced not only by salinity, but also by anthropogenic contaminants such as nutrients and fecal microorganisms. Nutrients such as ammonia, nitrate, and phosphate are commonly associated with domestic wastewater, septic tank leakage, livestock waste, fertilizer use, detergents, and other nutrient-rich sources [4, 6]. Nitrate is of particular concern because elevated concentrations in drinking water may pose health risks, especially for vulnerable populations [3, 7]. Ammonia and phosphate can also indicate organic pollution, wastewater infiltration, and nutrient enrichment in shallow groundwater systems [5, 6].

Microbiological contamination is another critical concern for groundwater used as a domestic water source. The presence of *Escherichia coli* indicates fecal contamination and suggests that pathogens from human or animal waste may have entered the groundwater system [4, 8]. Studies in Indonesia have shown that microbial contamination of shallow groundwater is associated with well type, poor well protection, sanitation conditions, proximity to septic systems, and local hydrogeological factors [9, 10]. In low-lying coastal settlements, shallow water tables and limited separation between wells and sanitation facilities can increase the risk that wastewater-derived nutrients and fecal bacteria migrate into domestic wells [11, 12].

Coastal aquifers require integrated assessment because nutrient enrichment, fecal contamination, seawater intrusion, and land-use pressures may occur simultaneously [5, 13-15]. Previous studies have shown that coastal groundwater contamination can reflect combined influences from domestic sewage, agriculture, aquaculture, and hydrogeochemical processes [14-16]. Therefore, groundwater assessment in coastal areas should not rely on a single parameter, but should consider chemical indicators, microbiological indicators, spatial position, and potential contamination sources together [6, 14, 17].

Geographic information systems, or GIS, provide an effective approach for assessing and visualizing spatial variation in groundwater quality. GIS-based groundwater studies can support the classification of water quality, identification of vulnerable zones, overlay analysis of potential sources, and spatial interpretation of contamination patterns [18-20]. By integrating laboratory measurements with information on well locations, distance from the coastline, and distance from sanitation facilities, GIS-based assessment can help identify areas where groundwater protection and sanitation improvement should be prioritized [18-20].

Tanah Laut Regency, South Kalimantan, contains coastal sub-districts such as Takisung, Panyipatan, Jorong, and Kintap, where shallow groundwater remains important for domestic use and where coastal settlements, sanitation systems, agriculture, and other land-use activities may place pressure on groundwater quality [21, 22]. Despite this vulnerability, spatially explicit information on nutrient contamination and *E. coli* occurrence in domestic wells in these coastal areas remains limited. This lack of integrated chemical, microbiological, and spatial information constrains local efforts to identify high-risk zones and design targeted groundwater protection strategies [18, 21, 22]. The groundwater-quality classification and scoring criteria used to evaluate nitrate, ammonia, phosphate, and E. coli are presented in Table 1. These criteria were applied consistently to classify the measured water-quality parameters into five quality levels.

This study addresses the following research question: How do nutrient concentrations and *E. coli* contamination vary spatially in shallow coastal groundwater in Takisung, Panyipatan, Jorong, and Kintap, and how can GIS-based assessment be used to identify groundwater vulnerability zones? The specific contribution of this study is the integration of laboratory measurements of ammonia, nitrate, phosphate, and *E. coli* with GIS-based spatial analysis of well locations, coastal proximity, and sanitation-related factors. By classifying groundwater quality and mapping contamination patterns, this study provides locally relevant evidence for groundwater protection, sanitation planning, and safer domestic water access in coastal Tanah Laut Regency.

Table 1. Clean water quality scoring

Classification	Nitrate (mg/L)	Ammonia (mg/L)	Phosphate (mg/L)	*E. coli* (CFU/100 mL)
Very Good (5)	≤ 10	≤ 0.1	≤ 0.3	0
Good (4)	>10 - 25	> 0.1 - 0.5	> 0.3 - 0.5	1 - 10
Moderate (3)	> 25 - 30	> 0.5 - 2	> 0.5 - 1.5	> 10 - 50
Poor (2)	> 30 - 50	> 2 - 8	> 1.5 - 2.5	> 50 - 100
Very Poor (1)	> 50	> 8	> 2.5	>100

Source: Studies [23-25].

2. METHODOLOGY

2.1 Location

The study was carried out in five coastal sub-districts of Tanah Laut Regency, South Kalimantan Province, Indonesia: Takisung, Panyipatan, Kurau, Jorong, and Kintap. These sub-districts are situated along the southern coastline of Borneo and are characterized by low-lying coastal plains, shallow unconfined aquifers, and a tropical monsoon climate with distinct wet and dry seasons. In these areas, households predominantly obtain their drinking and domestic water from shallow dug wells, as centralized piped water infrastructure is limited [2]. The proximity to the sea, combined with the hydrogeological characteristics of the coastal plain and the presence of settlements and agriculture, suggests that local aquifers may be vulnerable to nutrient contamination and other forms of groundwater degradation [26-28].

The repeated-measures design was selected because it allowed groundwater quality to be compared between seasons while maintaining the same sampling locations. This approach reduced location-related variability and enabled seasonal changes in nutrient concentrations and microbiological contamination to be evaluated more consistently. Therefore, each dry-season observation was matched with a corresponding wet-season observation from the same well.

2.2 Selection of wells and data collection

Domestic wells were selected using a purposive and stratified sampling strategy. The sampling frame consisted of wells reported by households as their primary source of drinking and household water in the five coastal sub-districts. Inclusion criteria required that wells be in active use, accessible for sampling, and located within a defined inland distance from the coastline. The resulting dataset consisted of 50 privately owned domestic wells paired observations and 100 total groundwater measurements (two seasons). This design enabled the study to evaluate both seasonal variation and spatial variability in groundwater quality in relation to distance from the coastline, distance from sanitation facilities, and other site-specific environmental conditions [29, 30]. A total of wells were selected, representing a range of hydrogeological and land use contexts within the study area [17, 31, 32].

The depths of the sampled wells varied between approximately 5 m and 15 m below ground level, reflecting common construction practices for domestic wells in the coastal plain. The study represents household groundwater sources along a coastal-to-inland gradient. Eligible wells were those used by households for daily clean water needs and located between approximately 100 m and 2 km from the coastline. This sampling range was intended to capture potential spatial variation in groundwater quality associated with increasing distance from the coast. During fieldwork, each well was assigned a unique sampling code, and its household address and geographical coordinates were recorded using a handheld global positioning system (GPS). The horizontal distance from each well to the coastline was subsequently calculated in a GIS environment using the recorded coordinates and coastal basemap data [33-35]. The distance between each well and the nearest sanitation facility, typically septic tanks or pit latrines, was measured in the field using measuring tapes, aided by GPS positioning and visual inspection, and confirmed through household interviews [25].

The wells were distributed across the coastal sub-districts as follows: Panyipatan, 10 wells; Takisung, 12 wells; Kurau, 9 wells; Jorong, 11 wells; and Kintap, 8 wells. All selected wells were actively used by households as daily clean-water sources and were accessible for repeated sampling during both the wet and dry seasons.

The study did not apply proportional allocation or sampling weights because the total population of household wells in each sub-district was not available. No official government or institutional database was available that recorded the number of private household wells by sub-district. Therefore, the sampling was conducted purposively to represent domestic wells located in accessible settlement areas along the coastal zone.

No wells were excluded from the final analysis. The same 50 wells were successfully sampled during both the wet and dry seasons, resulting in 100 seasonal groundwater observations. Each well was assigned a unique sampling code, and household address information and geographic coordinates were recorded to ensure that the same wells were revisited during the second sampling campaign.

The spatial distribution of wells was also influenced by the presence or absence of residential wells in the coastal landscape. As shown in Figure 1, there are relatively wide areas between Panyipatan and Jorong, as well as to the eastern part of Kintap, where no sampled wells are shown. These gaps do not represent omitted or excluded samples; rather, they reflect areas where household wells were not present or were not available for sampling.

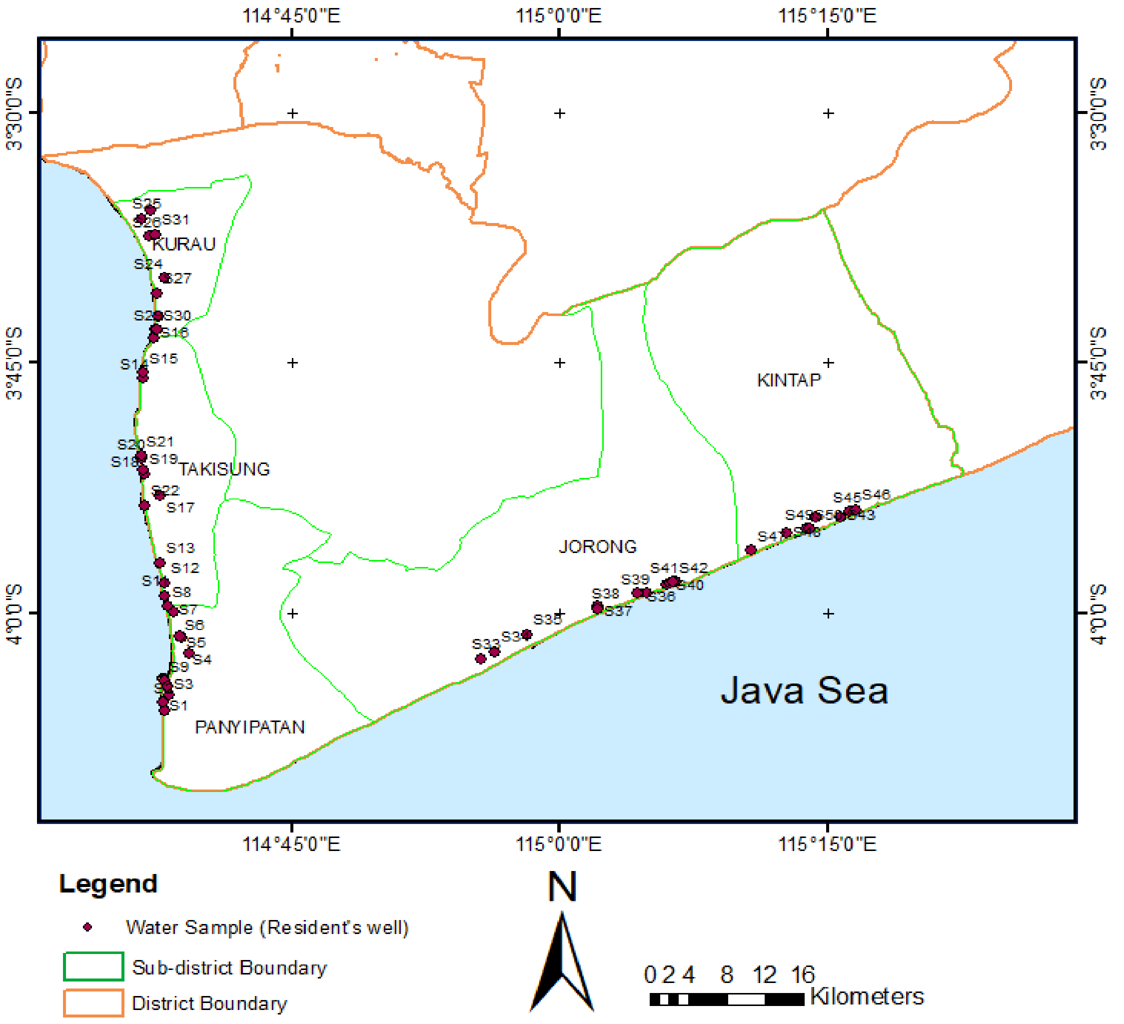


Figure 1. Research area and sample

2.3 Groundwater sampling and laboratory analysis

Groundwater sampling followed standard procedures to ensure that collected samples were representative of aquifer conditions and free from external contamination. Prior to sample collection, each well was purged by extracting water for several minutes to remove any stagnant water within the well shaft and to allow fresh groundwater to enter from the surrounding aquifer [36, 37].

Water samples were collected in appropriate containers for physicochemical analysis (Table 2). The key parameters measured in this study were ammonia, nitrate, and phosphate, chosen as indicators of nutrient contamination potentially derived from domestic wastewater, fertilizer use, and other anthropogenic sources [36, 37].

Groundwater samples were analyzed for nitrate, ammonia, phosphate, and *Escherichia coli* to assess chemical and microbiological contamination in domestic wells. Groundwater samples were collected in sterile containers, stored under controlled conditions, and transported to the Balai Besar Laboratorium Kesehatan Masyarakat (BBLKM) for analysis. All chemical and microbiological analyses were performed by BBLKM using the applicable Indonesian National Standards (SNI) and laboratory procedures accredited by the National Accreditation Committee (KAN).

Table 2. Sample wells data

No.	Depth (Meter)	Distance From		
		Sanitation Facilities (Meter)	Agricultural Land (Meter)	Coast (Meter)
S1	9	7	120	167,91
S2	17	17	115	231,40
S3	15	20	130	467,83
S4	10	5	130	1.760,00
S5	7	6	20	1.112,50
S6	13	13	150	1.005,30
S7	14	14	150	843,10
S8	15	15	150	353,59
S9	13	13	150	365,56
S10	20	18	150	850,88
S11	11	10	18	266,80
S12	7	5	12	613,79
S13	7	6	8	660,71
S14	15	15	20	448,28
S15	15	13	19	395,23
S16	15	13	19	361,92
S17	23	20	25	2.110,00
S18	9	7	30	454,54
S19	8	8	95	460,10
S20	11	14	30	590,11
S21	15	16	30	614,71
S22	12	22	100	208,22
S23	20	15	120	863,26
S24	17	17	20	2.790,00
S25	15	16	23	1.860,00
S26	17	15	12	1.210,10
S27	15	14	10	541,57
S28	17	18	15	611,47
S29	12	17	12	376,45
S30	14	15	150	125,06
S31	12	14	20	1.960,00
S32	13	13	25	326,14
S33	14	13	12	1.081,00
S34	10	21	12	1.020,00
S35	18	21	12	2.051,00
S36	11	13	15	351,77
S37	13	15	30	502,52
S38	10	13	12	245,50
S39	18	21	12	235,59
S40	10	13	30	344,62
S41	11	11	30	294,61
S42	10	10	20	356,66
S43	20	20	18	227,46
S44	15	15	17	1.080,00
S45	9	8	21	228,43
S46	10	10	20	191,25
S47	10	12	17	241,72
S48	11	12	8	473,56
S49	11	20	35	207,16
S50	19	19	25	107,10

For each parameter, the laboratory report included the analytical method, instrument used, wavelength, calibration range, limit of detection (LOD), limit of quantification (LOQ), duplicate measurement procedure, and quality-control results. *E. coli* was analyzed using SM APHA 23rd Edition, Method 9222 J:2017, and the results were reported as CFU/100 mL. Therefore, the *E. coli* analysis was based on a colony-count method rather than the MPN method. The maximum allowable value used for comparison was 0 CFU/100 mL. For example, sample MB.2025.12.4468 showed an *E. coli* concentration of 13 CFU/100 mL.

Quality assurance and quality control were implemented by the laboratory throughout the analysis. These procedures included calibration verification, reagent blanks, duplicate sample analysis, and compliance with method-specific acceptance criteria. The values of LOD, LOQ, calibration range, duplicate precision, and quality-control results for nitrate, ammonia, phosphate, and *Escherichia coli* are presented in Table 3 to ensure transparency and reproducibility of the analytical procedures.

Table 3. Laboratory quality parameters

Parameter	Unit	Maximum Level	Standard Analytical Method
Nitrat (NO_3^-)	mg/L	20	SM APHA, Section 4500-NO_3-B-2015
Amonia (NH_3)	mg/L	0	SNI 06-6989.30-2004
Phospat (PO_4)	mg/L	0	SNI 06-6989.31-2005
E. coli	CFU/ 100 mL	0	SM APHA 23rd Ed., 9222 J:2017

2.4 Statistical analysis

Statistical analyses were conducted using data from 50 matched domestic wells sampled during both the wet and dry seasons. Five additional records in the working dataset were excluded because they were not part of the final matched-well dataset. Therefore, the final analysis consisted of 50 paired wells and 100 seasonal groundwater observations.

Descriptive statistics were first calculated for nitrate, ammonia, and phosphate concentrations in each season. Spatial associations between distance from agricultural land and nutrient concentrations were evaluated using Spearman's rank correlation. Seasonal differences were analyzed using the Wilcoxon signed-rank test. Seasonal differences were analyzed as paired repeated measurements because the same wells were sampled in both seasons. The normality of paired seasonal differences was assessed using the Shapiro-Wilk test. Because the paired differences for nitrate, ammonia, and phosphate were not normally distributed, the Wilcoxon signed-rank test was used as the primary seasonal comparison test. Results were reported as sample size, test statistic, exact p-value, effect size using rank-biserial correlation, and 95% confidence interval for the median paired difference.

The distribution of nutrient concentrations and paired seasonal differences was assessed prior to statistical testing. Because the variables did not meet normality assumptions, Spearman's rank correlation was used to evaluate associations between agricultural land distance and nutrient concentrations, while the Wilcoxon signed-rank test was used to compare wet and dry season concentrations in the same wells. Results are reported as sample size (n), test statistic, exact P value, effect size, and 95% confidence interval.

2.5 Groundwater quality classification, spatial interpolation and overlay analysis

To evaluate groundwater quality in terms of nutrient contamination, measured concentrations of ammonia, nitrate, and phosphate were used to classify each well into one of five groundwater quality classes: very good, good, moderate, poor, and very poor. Classification thresholds for each parameter were based on national drinking-water standards and relevant literature on nutrient contamination in groundwater, with lower concentrations corresponding to higher quality classes and higher concentrations indicating increasing levels of nutrient enrichment and potential health and environmental risks. For each well, the combined nutrient profile was interpreted to assign a class that reflected its overall quality status within this five-level scheme [38, 39].

Spatial interpolation was conducted in ArcGIS 10.8 using the inverse distance weighting (IDW) method. Point data from 50 domestic wells, including coordinates and measured ammonia, nitrate, and phosphate concentrations, were projected to WGS 1984 UTM Zone 50S and interpolated separately for each parameter and season [40, 41]. IDW was selected because it estimates unsampled values from nearby measured points using distance-based weighting and does not require variogram modelling, which was considered appropriate for the limited and unevenly distributed well network [41].

The three interpolated surfaces for ammonia, nitrate, and phosphate were then overlaid to derive composite zones of nutrient contamination. Areas where all three parameters showed elevated values were interpreted as zones with a higher risk of nutrient-related groundwater degradation, while areas with consistently low concentrations across parameters were identified as relatively less impacted. The overlay analysis thus produced a map of pollution-prone zones that reflects the combined influence of ammonia, nitrate, phosphate and *E. coli* on coastal groundwater quality [42, 43].

Descriptive statistics were used to summarize the distribution of nutrient concentrations and groundwater quality classes across the 50 wells. Relationships between groundwater quality classes and explanatory variables such as distance to the coastline, well depth, and distance to sanitation facilities were explored using simple correlation and regression analyses. These statistical and spatial analyses provided a basis for identifying key factors associated with nutrient contamination in coastal groundwater and for discussing the implications of the findings for groundwater protection and SDG 6 implementation in Tanah Laut Regency [44, 45].

2.6 Ethical approval, informed consent, and privacy protection

This study received ethical approval from Universitas Indonesia under approval number KET-080/UN2.F13.D1.KE1/PPM.00/2025, dated 11 December 2025. Before data collection, all household respondents were informed about the study objectives, the type of information collected, and the confidentiality of personal and household-level data. Participation was voluntary, and household interviews were conducted using Google Forms.

3. RESULTS AND DISCUSSION

3.1 Spatial distribution of groundwater nutrient concentrations

The seasonal nitrate pattern may reflect the combined influence of dilution, leaching, and persistent anthropogenic inputs. Higher rainfall during the wet season may dilute nitrate in shallow groundwater, but it may also promote leaching of residual nitrogen from fertilizers, organic waste, and other surface-derived sources into the aquifer [43]. Conversely, during the dry season, reduced recharge and increased evapotranspiration may contribute to higher nitrate concentrations, while lower rainfall may reduce nitrogen leaching from the soil surface [42]. These opposing processes may explain why nitrate concentrations remained within a comparable range between seasons. However, because rainfall intensity, groundwater level, infiltration rate, redox condition, groundwater flow direction, and pumping intensity were not directly measured, dilution, leaching, and evaporative concentration should be regarded as possible explanations rather than confirmed mechanisms. Similar seasonal patterns have been reported in agricultural groundwater systems, where anthropogenic inputs such as fertilizer, livestock manure, and domestic waste may have a stronger influence than short-term seasonal variability [44].

The land-use distribution of the study area is presented in Figure 2. The map shows that residential areas are located near agricultural land and aquaculture areas, providing spatial context for interpreting the observed groundwater-quality patterns. Figure 3 shows a more heterogeneous pattern for ammonia parameters compared to nitrate, with some wells remaining in the good to excellent category (marked in light and dark blue), while others shifted to the moderate to poor category (yellow to orange). This variation indicates that the formation and transformation of ammonia in the Tanah Laut coastal aquifer is highly dependent on local hydrogeological conditions and the intensity of anthropogenic activities, particularly fertilization practices and domestic waste disposal. During the rainy season, the increase in the number of points in the lower quality category reflects the accumulation of ammonia originating from the decomposition of organic matter and nitrogen fertilizers that have not been fully oxidized to nitrate, particularly in shallow aquifers with redox conditions that tend to be reductive. Nitrogen transformation in groundwater is strongly influenced by redox (reduction-oxidation) conditions, thus potentially accumulating ammonia in zones with limited oxygen circulation and low oxidation capacity [45].

Conversely, during the dry season, ammonia quality was observed in a number of wells, as indicated by a shift in the category toward blue. This phenomenon can be attributed to increased ammonia oxidation to nitrate as the groundwater level drops and the aeration zone thickness increases, increasing the opportunity for contact between water and oxygen. However, in several locations hydrogeologically trapped in reductive conditions or subjected to continuous domestic and livestock waste, ammonia levels remained in the moderate to poor category. This condition indicates multiple sources of contamination, originating not solely from agricultural fertilizer residues but also from household waste and livestock activities around the wells [46].

Figure 3 shows significant spatial and temporal variations in phosphate levels between the rainy and dry seasons. During the rainy season, phosphate levels tend to increase in coastal zones with high activity levels, reflected in the dominance of moderate to very poor quality classes (categories 3–1) in several coastal sub-districts. This condition indicates that surface phosphate input from agricultural activities, settlements, and coastal tourism exceeds the natural dilution and filtration capacity of shallow aquifers. This pattern aligns with the findings of various studies in tropical coastal areas, which show that increased rainfall strengthens surface runoff and accelerates phosphate transport from land to shallow groundwater systems [47, 48].

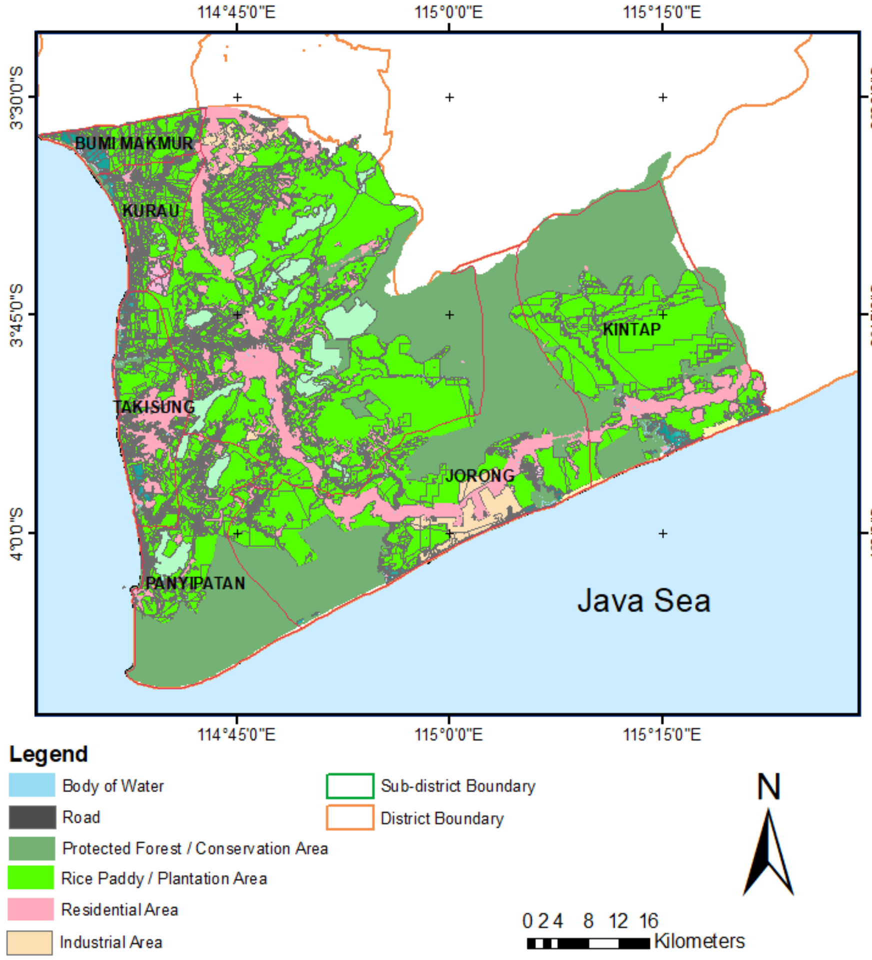


Figure 2. Land use of Tanah Laut
Source: Regional Development Agency

Conversely, during the dry season, the distribution pattern of residual phosphate shifts significantly. Several areas that were in the moderate to poor category during the rainy season gradually improved in quality to good to excellent (categories 4–5), as illustrated by the dominance of light and dark blue colors in several coastal segments. Similar phenomena have been reported in coastal hydrological studies that emphasize the role of seasonal rainfall variability on the dynamics of nutrient concentrations in groundwater, where the dry season tends to produce a pattern of stabilization or decrease in phosphate levels after the peak load during the rainy season [49, 50].

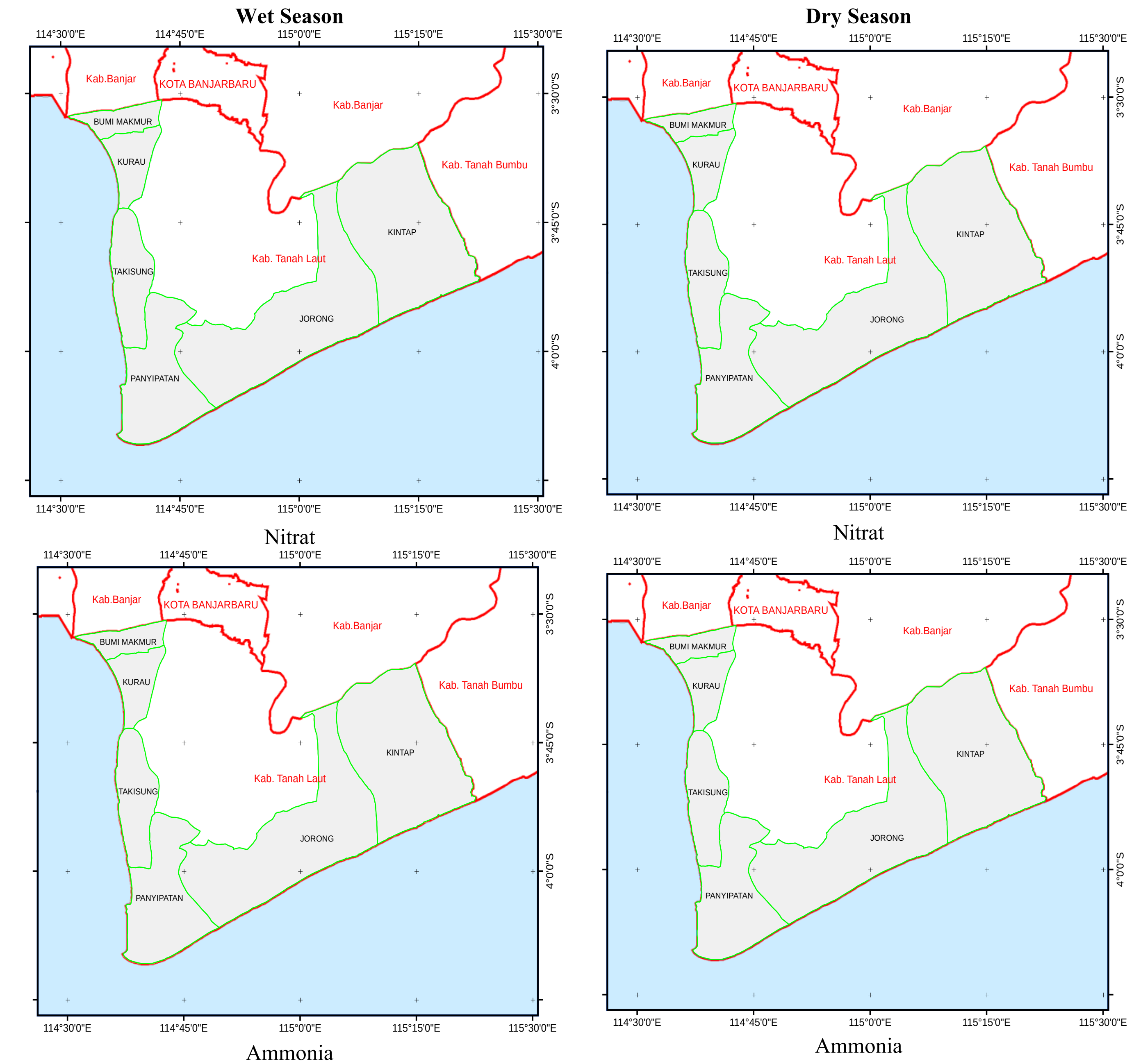
From a hydrogeological perspective, the seasonal variations depicted in the map can be interpreted as a manifestation of the balance between recharge and discharge processes in shallow coastal aquifer systems. During the rainy season, intensive rainwater infiltration increases recharge volume while accelerating the movement of phosphate from the topsoil toward the saturated zone. Consequently, although groundwater volume increases, phosphate concentrations increase, particularly in locations with high nutrient loads. As explained by Foster and Chilton [51] and furthered in various coastal groundwater studies, shallow aquifers in tropical coastal areas are highly susceptible to nutrient contamination due to their relatively shallow depth and proximity to surface pollution sources. During the dry season, decreased rainfall and reduced runoff result in fewer new phosphate inputs, so that phosphate concentrations are largely determined by release mechanisms, lateral flow, and well water pumping, which can help reduce nutrient loads in some locations.

Consistent with the literature, exposure to nitrate and ammonia at concentrations exceeding drinking water quality standards is associated with an increased risk of methemoglobinemia, impaired thyroid function, and the potential formation of carcinogenic N-nitroso compounds in the human body [52, 53]. In the context of the Tanah Laut coastal area, which relies heavily on well water, the presence of a number of wells of moderate to very poor quality directly increases public health vulnerabilities, particularly among children, pregnant women, and the elderly. Furthermore, the accumulation of phosphate and nitrate leaching from aquifers into surface water bodies can accelerate eutrophication, reduce dissolved oxygen levels, and damage coastal ecosystems, ultimately leading to reduced productivity of capture fisheries and aquaculture, which are sources of livelihood for local communities [54].

Normatively, these findings relate to the obligation of local governments and agricultural businesses to implement the precautionary principle in fertilizer use and environmental quality management, as stipulated in various national regulations regarding water resource management and environmental protection. From the perspective of environmental law and Islamic jurisprudence, fertilization practices that lead to well water pollution can be viewed as a violation of the principle of la darar wa la dirar (not causing harm to oneself or others). Therefore, a policy approach is needed that integrates positive legal instruments, administrative oversight, and the internalization of religious values into the ecological behavior of communities and businesses [53, 55].

Based on the identified seasonal contamination patterns, one key strategy that can be developed is the implementation of site-specific nutrient management, which regulates the dosage, timing, and method of fertilizer application to meet plant needs while minimizing nutrient loss to the environment. This practice includes, among other things, avoiding fertilizer application before or during forecasted high rainfall to reduce the risk of leaching and runoff of fertilizer residues into shallow aquifers [55]. On the other hand, the construction and rehabilitation of wells with more protective construction, such as the installation of concrete rings, well covers, and drainage channels that divert surface water away from the well rim, will help cut off the entry of contaminated water into wells used as domestic drinking water sources.

In addition to technical interventions, a program for regular monitoring of well water quality during both seasons should be developed so that communities have sufficient information to determine safe drinking water sources and plan preventative measures, such as the use of simple filtration technology or the use of alternative water sources. At the policy level, the results of the spatial analysis compiled in this study can provide a basis for local governments to establish wellhead protection zones, regulate land use around wells, and develop local regulations prohibiting waste disposal or fertilizer storage within a certain radius of the water source. These steps align with the recommendations of Carpenter et al. [54] and Sharpley et al. [56], which emphasize the importance of integrating nutrient management on agricultural land with water quality protection to prevent aquatic ecosystem degradation.



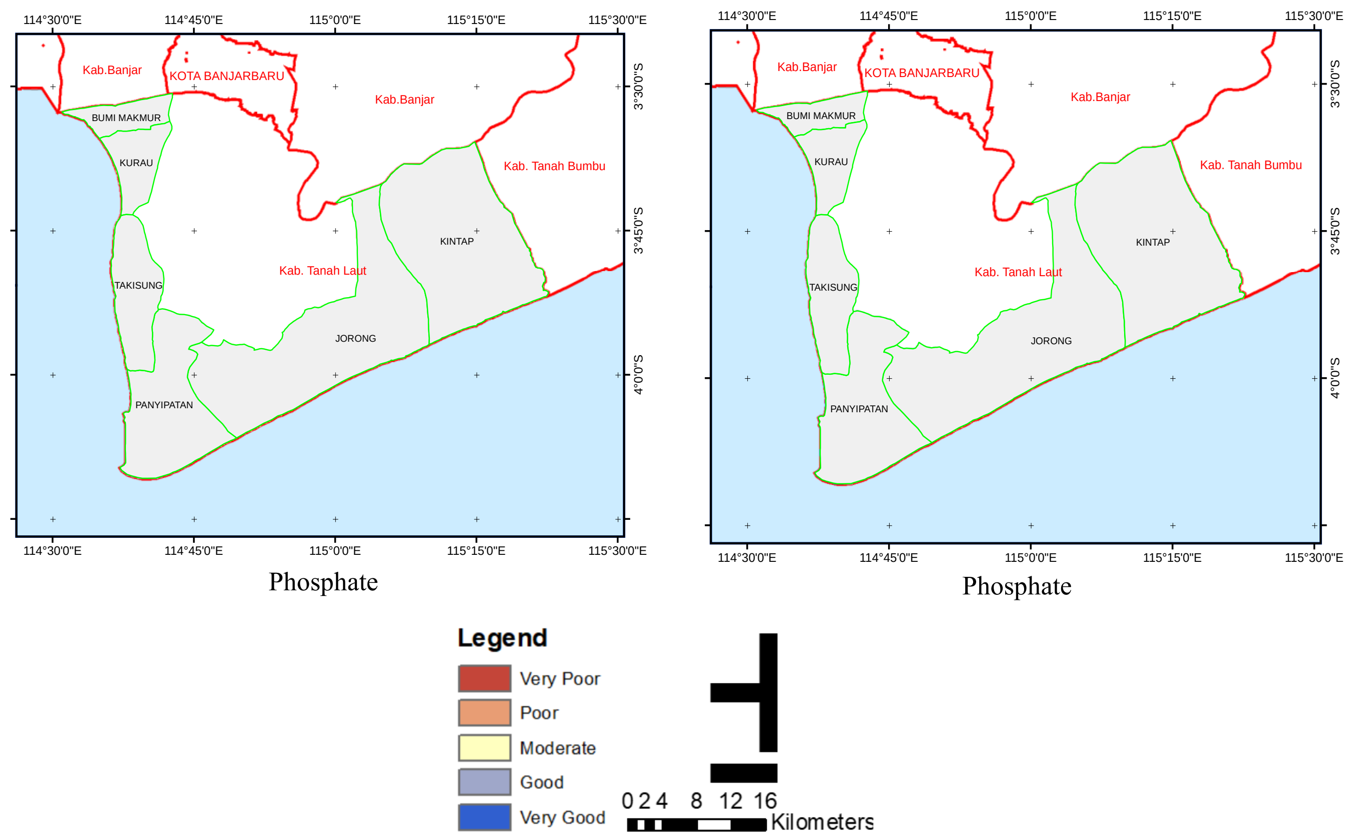


Figure 3. Fertilizer contamination indication map in clean water wells

3.2 Spatial distribution of *E. coli* contamination

Clean water in the coastal areas of Tanah Laut Regency generally comes from dug wells and shallow boreholes, which are highly susceptible to contamination from the surrounding environment. Clean water quality mapping was conducted to identify the spatial distribution of water quality parameters such as *E. coli* and nitrate in various coastal villages.

Previous research showed that well water quality varies between locations, with some villages having higher levels of contamination than others [57, 58]. This variation is influenced not only by hydrogeological characteristics but also by distance from pollution sources and human activity in the surrounding area. Field research and laboratory tests were conducted twice, during the dry and rainy seasons. The test results are shown in Figure 3.

The coastal areas of Tanah Laut Regency have hydrogeological characteristics that are vulnerable to pollution, particularly due to the interaction between shallow groundwater and ocean dynamics. This situation is further complicated by anthropogenic pressures, particularly from domestic activities in densely populated coastal areas. Impermeable sanitation systems, such as conventional septic tanks, act as a major source of fecal contamination, which then infiltrates shallow wells [47].

Field research revealed that wells are shallow and relatively close to septic tanks. Furthermore, the distance between houses is quite dense. Spatial analysis, shown in the map, also revealed a correlation between residential density and *E. coli* contamination levels. Areas with high domestic activity density tended to exhibit consistently lower water quality levels across both seasons. These findings align with research findings [59], which stated that exposure to *E. coli* contamination in clean water is significantly influenced by sanitation conditions and community behavior regarding domestic waste management.

Thus, the interpretation of these research results confirms that *E. coli* contamination in well water in the coastal area of Tanah Laut is a multidimensional phenomenon influenced by seasonal variability and community sanitation. A partial management approach will not be effective in reducing the risk of contamination, requiring an integrated strategy that includes protecting water sources, improving sanitation systems, and continuous spatial and temporal monitoring of water quality.

Table 4. Spatial association between agricultural land distance and groundwater nutrient concentrations

Parameter	Season	n	Test	Statistic	Exact P Value	Effect Size	95% CI
Nitrate	Wet	50	Spearman correlation	$\rho = -0.262$	0.066020	Weak negative	-0.524 to 0.037
Nitrate	Dry	50	Spearman correlation	$\rho = -0.255$	0.074246	Weak negative	-0.504 to 0.027
Ammonia	Wet	50	Spearman correlation	$\rho = -0.080$	0.582657	Very weak negative	-0.352 to 0.211
Ammonia	Dry	50	Spearman correlation	$\rho = -0.205$	0.153903	Weak negative	-0.465 to 0.067
Phosphate	Wet	50	Spearman correlation	$\rho = -0.943$	1.41×10^{-24}	Very strong negative	-0.971 to -0.878
Phosphate	Dry	50	Spearman correlation	$\rho = -0.889$	6.73×10^{-18}	Very strong negative	-0.953 to -0.776

Table 5. Seasonal comparison of nutrient concentrations in matched wells

Parameter	Wet Season, Mean ± SD	Wet Season, Median (IQR)	Dry Season, Mean ± SD	Dry Season, Median (IQR)	n	Test	Statistic	Exact P Value	Effect Size	Median paired Difference, Dry Minus Wet (95% CI)
Nitrate	4.63 ± 4.82	3.31 (1.20 to 6.16)	5.69 ± 6.24	4.30 (1.28 to 7.92)	50	Wilcoxon signed-rank	W = 171.0	0.006458	$r_{r\beta}$ = -0.514	-0.270 (-0.435 to 0.000)
Ammonia	0.20 ± 0.41	0.03 (0.03 to 0.03)	0.43 ± 0.86	0.03 (0.03 to 0.60)	50	Wilcoxon signed-rank	W = 78.0	0.192199	$r_{r\beta}$ = 0.325	0.000 (0.000 to 0.000)
Phosphate	1.88 ± 1.58	1.44 (0.49 to 3.00)	1.55 ± 1.40	1.19 (0.21 to 2.70)	50	Wilcoxon signed-rank	W = 0.0	2.41×10^{-7}	$r_{r\beta}$ = -1.000	-0.277 (-0.410 to -0.050)

3.3 Relationship between agricultural land distance and groundwater quality parameters

The relationship between groundwater quality and agricultural land was evaluated using the distance from each well to the nearest agricultural land boundary, rather than distance to the centre of agricultural fields. The distance was calculated in a GIS environment using the recorded well coordinates and the mapped agricultural land-use layer. The land-use map added to the Results section shows that residential areas in the coastal sub-districts are spatially close to rice fields, plantation areas, and coastal aquaculture ponds. This spatial configuration indicates that many domestic wells are located within settlement areas that are directly adjacent to agricultural and pond-based production activities. Therefore, the variable is described as proximity to agricultural land, not direct fertilizer exposure (Figure 2).

Field observations also indicated that the coastal communities in the study area are commonly engaged in farming and aquaculture-related livelihoods. Both activities may involve the use of nitrogen- and phosphorus-containing inputs, including fertilizers and pond management materials. However, because no farm-level fertilizer application records were available, the analysis does not quantify fertilizer exposure directly. Instead, agricultural proximity is used as a spatial indicator of potential influence from nearby cultivated land and aquaculture-associated activities.

Because the nutrient variables and paired seasonal differences were not normally distributed, the association between agricultural land proximity and groundwater quality parameters was evaluated using Spearman's rank correlation. All analyses were conducted using the 50 matched wells sampled in both wet and dry seasons. The spatial associations between proximity to agricultural land and groundwater nutrient concentrations in both seasons are summarized in Table 4.

Distance from agricultural land showed a negative association with nitrate concentration in both seasons, although the relationship was not statistically significant at the 0.05 level. In the wet season, nitrate showed a weak negative correlation with distance from agricultural land boundary (Spearman's ρ = -0.262, P = 0.066, 95% CI: -0.524 to 0.037). A similar pattern was observed in the dry season (ρ = -0.255, P = 0.074, 95% CI: -0.504 to 0.027). These findings suggest a tendency for wells located closer to agricultural land to have higher nitrate concentrations, although the statistical evidence was not sufficient to confirm a significant spatial association.

Ammonia showed weak and non-significant correlations with agricultural distance in both seasons. The correlation was very weak in the wet season (ρ = -0.080, P = 0.583, 95% CI: -0.352 to 0.211) and remained non-significant in the dry season (ρ = -0.205, P = 0.154, 95% CI: -0.465 to 0.067). This indicates that ammonia variability was not primarily explained by proximity to agricultural land. Instead, ammonia concentrations may be influenced by localized processes, including organic matter decomposition, microbial transformation, domestic wastewater inputs, and well-specific environmental conditions.

The strongest and most consistent spatial relationship was observed for phosphate. Phosphate concentration was strongly and inversely correlated with distance from the agricultural land boundary in both the wet season (ρ = -0.943, P = 1.41×10^{-24}, 95% CI: -0.971 to -0.878) and dry season (ρ = -0.889, P = 6.73×10^{-18}, 95% CI: -0.953 to -0.776). These results indicate that wells located closer to agricultural land consistently had higher phosphate concentrations. The spatial pattern is consistent with the land-use map, which shows that settlement areas and domestic wells are located near agricultural and aquaculture areas. Thus, phosphate enrichment in shallow groundwater may be related to the proximity of wells to land-use activities that commonly involve phosphorus-containing inputs, although direct fertilizer loading was not measured in this study.

Overall, the results show that proximity to agricultural land was most strongly associated with phosphate concentrations, while nitrate showed only a weak and non-significant tendency and ammonia showed no clear spatial pattern. These findings suggest that agricultural land proximity is an important spatial indicator for assessing groundwater nutrient risk, particularly for phosphate, but should not be interpreted as direct evidence of fertilizer exposure without supporting fertilizer application data.

Seasonal comparisons of nitrate, ammonia, and phosphate concentrations in the 50 matched wells are presented in Table 5. Because the paired differences were not normally distributed, the Wilcoxon signed-rank test was used as the primary seasonal test. Nitrate had a higher mean concentration in the dry season than in the wet season; however, because the distribution was skewed, the Wilcoxon signed-rank test was used as the primary test. The paired comparison indicated a significant seasonal shift in nitrate concentrations (W = 171.0, P = 0.006458, rank-biserial correlation = -0.514), with a median paired difference of -0.270 mg/L for dry minus wet season values. The median paired difference of −0.270 mg/L was calculated from the dry-minus-wet difference within each matched well and is therefore not equivalent to the difference between the overall seasonal medians. The apparent difference in direction reflects the skewed distribution of the paired changes and the influence of several relatively large dry-season nitrate values on the overall mean.

Ammonia increased in mean concentration from the wet season to the dry season, but the paired seasonal difference was not statistically significant (W = 78.0, P = 0.192199, rank-biserial correlation = 0.325). The median paired difference was 0.000 mg/L, indicating that most wells showed little seasonal change in ammonia concentration.

Phosphate showed a clear seasonal decrease from the wet season to the dry season. The Wilcoxon signed-rank test confirmed a significant seasonal difference (W = 0.0, P = 2.41 × 10^{-7}, rank-biserial correlation = -1.000), with a median paired difference of -0.277 mg/L for dry minus wet season values. This indicates that phosphate concentrations were consistently higher during the wet season, suggesting that rainfall-driven runoff and leaching from agricultural land may enhance phosphate transport into shallow groundwater.

Overall, the results indicate that phosphate was the nutrient most strongly associated with proximity to agricultural land and showed a significant seasonal response. Nitrate showed a weak negative relationship with agricultural distance and a statistically significant seasonal shift, but the direction of seasonal change should be interpreted carefully because mean and paired-rank patterns differed. Ammonia showed no clear spatial or seasonal pattern, suggesting that its concentration was more likely influenced by localized well conditions and biogeochemical processes than by agricultural distance alone.

3.4 Distribution of *E. coli* contamination in groundwater

E. coli contamination was evaluated as a microbiological indicator of fecal contamination in the 50 matched domestic wells sampled during the wet and dry seasons. Because the drinking-water requirement for *E. coli* is zero detection in a 100 mL sample, any detectable *E. coli* concentration was classified as microbiologically non-compliant. The uploaded dataset includes well depth, distance to sanitation facilities, distance to the coast, sub-district location, and wet- and dry-season *E. coli* concentrations for all 50 wells.

The descriptive results show that *E. coli* contamination was widespread in both seasons, although concentrations were generally higher during the wet season. In the wet season, *E. coli* was detected in 48 of 50 wells, equivalent to 96.0% of samples. Concentrations ranged from 0 to 201, with a mean of 68.18 ± 58.01 and a median of 60.0. In the dry season, *E. coli* was detected in 44 of 50 wells, equivalent to 88.0% of samples. Dry-season concentrations ranged from 0 to 190, with a mean of 53.16 ± 54.97 and a median of 37.5. These results indicate that most wells did not meet the zero-detection requirement in either season, although both the proportion of positive wells and the median concentration were lower in the dry season. The seasonal and sub-district distributions of E. coli-positive wells, descriptive concentrations, and compliance with the zero-detection standard are summarized in Table 6.

Sub-district patterns showed that *E. coli* contamination occurred across all coastal areas, but the magnitude varied. Takisung showed consistently high contamination, with all sampled wells positive in both seasons and median values of 72.5 in the wet season and 50.0 in the dry season. Kurau and Kintap also showed complete or near-complete detection across seasons, although their median concentrations were lower than those in Takisung. Panyipatan had the lowest proportion of E. coli-positive wells, decreasing from 8 of 10 wells (80.0%) in the wet season to 7 of 10 wells (70.0%) in the dry season. Accordingly, two wells met the zero-detection requirement in the wet season, compared with three wells in the dry season. In Jorong, all wells were positive in the wet season, but three wells met the zero-detection requirement during the dry season.

Table 6. Seasonal and sub-district distribution of *E. coli* contamination in domestic wells

Area / Season	n	Positive Wells, n (%)	Wells Meeting Zero-Detection Standard, n (%)	Mean ± SD	Median	Range
Wet season, all wells	50	48 (96.0%)	2 (4.0%)	68.18 ± 58.01	60.0	0–201
Dry season, all wells	50	44 (88.0%)	6 (12.0%)	53.16 ± 54.97	37.5	0–190
Panyipatan, wet	10	8 (80.0%)	2 (20.0%)	72.20 ± 91.11	14.0	0–201
Panyipatan, dry	10	7 (70.0%)	3 (30.0%)	64.50 ± 85.06	10.0	0–190
Takisung, wet	12	12 (100.0%)	0 (0.0%)	97.00 ± 70.34	72.5	3–201
Takisung, dry	12	12 (100.0%)	0 (0.0%)	75.00 ± 62.27	50.0	10–175
Kurau, wet	9	9 (100.0%)	0 (0.0%)	45.89 ± 18.54	46.0	20–72
Kurau, dry	9	9 (100.0%)	0 (0.0%)	39.11 ± 25.49	30.0	15–80
Jorong, wet	11	11 (100.0%)	0 (0.0%)	57.82 ± 21.28	65.0	25–85
Jorong, dry	11	8 (72.7%)	3 (27.3%)	36.00 ± 35.09	21.0	0–80
Kintap, wet	8	8 (100.0%)	0 (0.0%)	59.25 ± 41.46	51.5	25–150
Kintap, dry	8	**8 (100.0%)**	**0 (0.0%)**	45.63 ± 38.40	35.0	5–120

Note: Positive wells are wells with detectable *E. coli* > 0. Values should be reported using the same unit as the laboratory report, for example, CFU/100 mL.

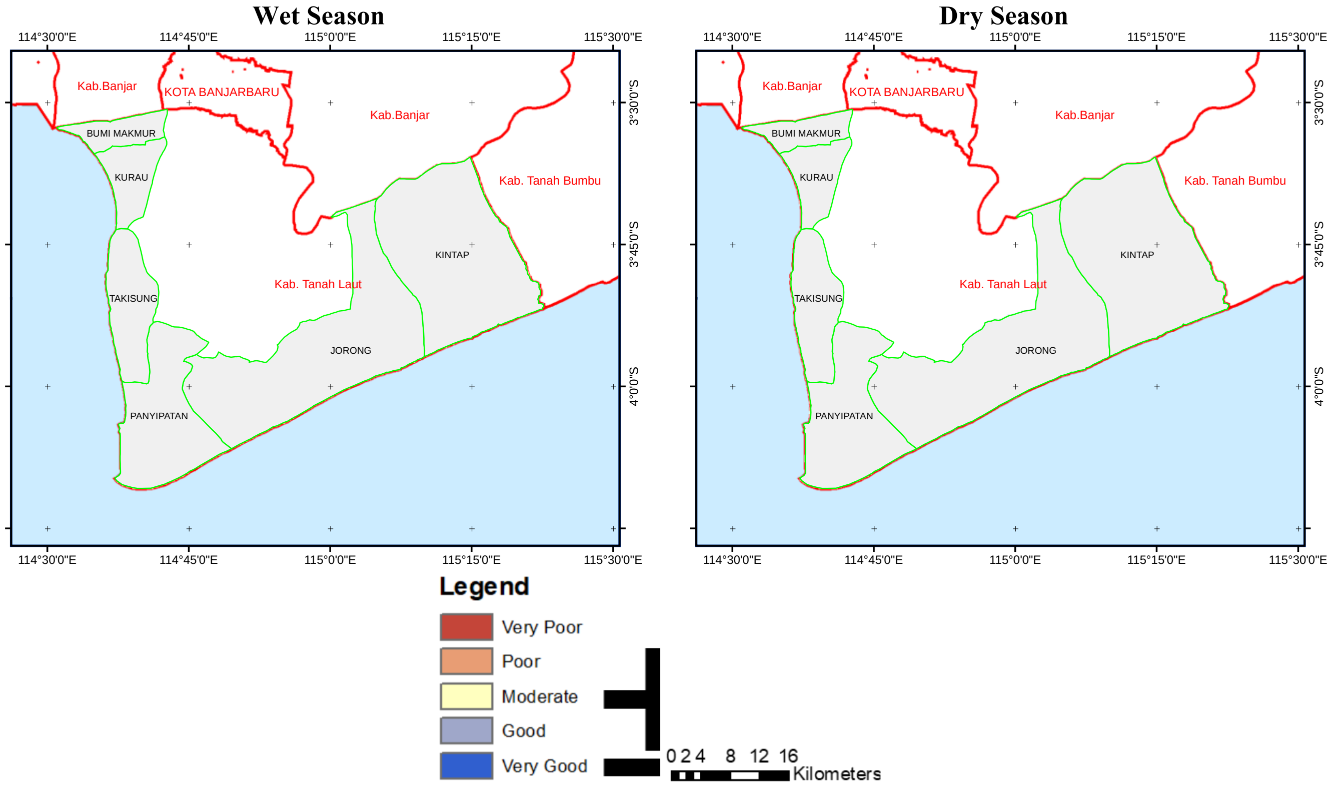


Figure 4. *E. coli* contamination map in clean water wells

Table 7. Leave-one-out cross-validation results for inverse distance weighting (IDW) interpolation of groundwater nutrient parameters

Parameter	Season	n	IDW Power	Search Neighbourhood	Cell Size	Mean Error	RMSE	Interpretation
Nitrate	Wet season	50	2			0.444	5.884	Low positive bias, but relatively high prediction error, indicating strong local variability in wet-season nitrate.
Nitrate	Dry season	50	2			0.290	6.398	Low prediction bias, but the highest RMSE among nutrient models, suggesting heterogeneous dry-season nitrate distribution.
Ammonia	Wet season	50	2	Variable circular, 12 nearest neighbours	50-100 m	0.006	0.323	Mean error was close to zero, indicating very low bias; RMSE was also relatively low in absolute terms.
Ammonia	Dry season	50	2			0.004	0.521	Very low bias, but higher RMSE than wet-season ammonia, suggesting more localized dry-season variation.
Phosphate	Wet season	50	2			0.236	1.585	Moderate positive bias and relatively high RMSE, indicating spatial variability in wet-season phosphate.
Phosphate	Dry season	50	2			0.260	1.369	Moderate positive bias, with slightly better predictive accuracy than wet-season phosphate based on lower RMSE.

Note: RMSE: Root Mean Square Error.

A paired seasonal comparison indicated that *E. coli* concentrations decreased from the wet season to the dry season. The median paired difference, defined as dry minus wet season concentration, was -11.0, and the Wilcoxon signed-rank test showed a significant seasonal decrease ($n = 50$, $W = 120.0$, $p < 0.001$, rank-biserial correlation = -0.758, 95% CI: -20.0 to -6.0). At the well level, *E. coli* concentrations decreased in 36 wells, increased in 8 wells, and remained unchanged in 6 wells. This seasonal reduction suggests lower microbiological loading or reduced transport during the dry season, although the high proportion of positive wells in both seasons indicates persistent fecal contamination risk.

The relationship between *E. coli* and sanitation proximity was also evaluated. *E. coli* concentrations showed a strong negative correlation with distance to sanitation facilities in both the wet season (Spearman's $\rho = -0.762$, $p < 0.001$) and dry season ($\rho = -0.662$, $p < 0.001$). This means that wells located closer to sanitation facilities tended to have higher *E. coli* concentrations. A descriptive comparison further supported this pattern: all 11 wells located within 10 m of sanitation facilities were *E. coli*-positive in both seasons, with median concentrations of 180.0 in the wet season and 150.0 in the dry season. In contrast, wells located more than 10 m from sanitation facilities had lower median concentrations, namely 46.0 in the wet season and 21.0 in the dry season.

The spatial distribution of observed E. coli contamination during the wet and dry seasons is presented in Figure 4. The figure represents classified sampling points rather than an IDW-interpolated surface or an administrative-area summary.

3.5 Distribution of *E. coli* contamination in groundwater

The IDW cross-validation results showed that all models produced mean error values close to zero, indicating limited systematic prediction bias. Ammonia had the lowest absolute mean error in both seasons, with mean errors of 0.006 mg/L in the wet season and 0.004 mg/L in the dry season. However, dry-season ammonia produced a higher Root Mean Square Error (RMSE) than wet-season ammonia, suggesting greater local variability during the dry season, as summarized in Table 7.

Nitrate showed the highest RMSE values among the three nutrient parameters. The RMSE increased from 5.884 mg/L in the wet season to 6.398 mg/L in the dry season, indicating that nitrate was less spatially predictable than ammonia and phosphate. This pattern is consistent with the heterogeneous distribution of nitrate among wells, particularly where several wells showed unusually high dry-season concentrations. For phosphate, the RMSE decreased from 1.585 mg/L in the wet season to 1.369 mg/L in the dry season. This indicates that the dry-season phosphate surface had slightly better predictive performance than the wet-season surface. Nevertheless, phosphate showed moderate positive mean error in both seasons, suggesting that the IDW model tended to slightly underpredict observed phosphate concentrations when error was defined as observed minus predicted value.

Overall, the cross-validation results indicate that the IDW surfaces are suitable for exploratory visualization of groundwater quality patterns, but the relatively high RMSE values for nitrate and phosphate suggest that the interpolated maps should be interpreted cautiously. The maps should therefore be used to identify broad spatial tendencies and priority monitoring zones rather than to infer precise concentration values at unsampled locations.

4. CONCLUSIONS

This study found that coastal domestic wells in Tanah Laut Regency showed observed spatial and seasonal associations with nutrient and fecal contamination indicators. Nitrate and phosphate concentrations tended to be higher in wells located closer to agricultural land, with phosphate showing the strongest and most consistent spatial association. Seasonal analysis also indicated higher phosphate concentrations during the wet season, suggesting that rainfall-related mobilization may influence nutrient patterns in shallow groundwater. However, because this study used an observational seasonal repeated-measures design, these findings should be interpreted as associations rather than direct causal evidence of fertilizer use, settlement density, sanitation conditions, or seasonal hydrological processes.

The detection of *E. coli* in groundwater indicates microbiological concern and highlights the need for improved local risk management around domestic wells. Practical recommendations should therefore focus on strengthening wellhead protection, maintaining safe separation distances between wells and sanitation facilities, improving household sanitation practices, and conducting follow-up testing of priority wells, especially those located near agricultural land or sanitation sources. These actions can support safer domestic water use in coastal communities.

The findings are relevant to the objectives of SDG 6 because they provide local evidence on groundwater quality risks and help identify areas where groundwater protection and sanitation improvements should be prioritized. However, this study did not calculate formal SDG 6 indicators, and therefore its contribution should be understood as supporting local evidence for SDG 6-related planning rather than as a direct assessment of SDG 6 achievement. Future research should include longer-term monitoring, broader hydrogeological measurements, microbial and nutrient source-tracing, and expanded spatial coverage to better distinguish agricultural, domestic, and natural contributions to groundwater contamination.

This study has several limitations. Although the same wells were sampled during the wet and dry seasons, the observational design only supports the identification of spatial and seasonal associations and does not establish causal pathways. Several relevant hydrogeological variables were not directly measured, including groundwater flow direction, hydraulic gradient, hydraulic conductivity, soil texture, aquifer thickness, lithology, water-table fluctuation, and recharge rate. Therefore, the observed associations between groundwater quality parameters, agricultural proximity, sanitation distance, and season should be interpreted as indicators of potential vulnerability rather than direct evidence of contaminant sources or transport pathways.

The study measured well depth, well coordinates, distance to the coastline, distance to sanitation facilities, distance to agricultural land boundary, and seasonal concentrations of nitrate, ammonia, phosphate, and *E. coli*. However, source-specific information such as fertilizer application rates, septic tank construction, septic leakage, aquaculture inputs, and microbial source-tracing data was not available. Consequently, the contribution of agricultural, domestic, aquaculture, and natural sources could not be separated with certainty. Future studies should include continuous groundwater-level monitoring, hydrogeological characterization, soil and sediment analysis, rainfall and recharge data, and source-tracing methods to better explain contaminant pathways in shallow coastal aquifers.

DATA AVAILABILITY STATEMENT

Personal identifiers were removed from the analytical dataset. Respondent identity, age, sex, occupation, exact household address, and precise well coordinates were not disclosed because these data are private and protected under applicable Indonesian personal data protection regulations, including Law No. 27 of 2022 on Personal Data Protection. Detailed laboratory results were used in the analysis but are not fully presented in the manuscript to maintain conciseness. De-identified analytical data may be made available from the corresponding author upon reasonable request, subject to ethical approval conditions and privacy restrictions.

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