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Spatial Distribution of Household Water Contamination Associated with Livestock Waste Along Upstream-Downstream Areas in Ponorogo, Indonesia

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A B S T R A C T

Livestock waste is a major source of environmental pollution in rural Indonesia. In general, livestock sanitation and household water quality are still assessed separately, so understanding of contamination pathways in upstream and downstream hydrological systems remains limited. This study aims to explore the spatial distribution of household water contamination associated with livestock waste sanitation and to classify environmental health risks along an upstream-downstream gradient. An exploratory environmental assessment was conducted in three descriptive sub-districts of Ponorogo Regency, representing the upstream (Pudak), transition (Pulung), and downstream (Sooko) areas. Fifteen household water samples were analyzed for microbiological parameters (total *coliforms*, *Escherichia coli*) and chemical parameters (BOD, nitrates, NH3), as well as for secondary data on cattle pen sanitation and river water quality. Data were analyzed descriptively and spatially using semi-quantitative risk classification based on exceeding national quality standards. 58% of cattle pens lacked adequate sanitation. BOD levels reached 14 mg/L (which was 2.33 times higher than the national standard), and NH_3 reached 0.64 mg/L (32 times higher). None of the household water samples were eligible for total microbiological testing. Gradients of increased contamination in upstream areas (Pudak) with moderate pollution loads, transition areas (Pulung) with moderate levels of contamination due to upstream exposure, and downstream (Sooko) with high contamination. Contamination patterns show an increased risk gradient from upstream to downstream waste sources. Improving cattle pen sanitation and livestock waste management in upstream areas is needed as a priority for environmental health interventions.

Limbah ternak merupakan sumber utama pencemaran lingkungan di pedesaan Indonesia. Secara umum, sanitasi ternak dan kualitas air rumah tangga masih dinilai secara terpisah, sehingga pemahaman tentang jalur kontaminasi di sistem hidrologi hulu dan hilir masih terbatas. Studi ini bertujuan untuk mengeksplorasi distribusi spasial kontaminasi air rumah tangga yang terkait dengan sanitasi limbah ternak dan untuk mengklasifikasikan risiko kesehatan lingkungan di sepanjang gradien hulu-hilir. Penilaian lingkungan eksploratif dilakukan di tiga kecamatan deskriptif Kabupaten Ponorogo, yang mewakili daerah hulu (Pudak), transisi (Pulung), dan hilir (Sooko). Lima belas sampel air rumah tangga dianalisis untuk parameter mikrobiologis (koliform total, Escherichia coli) dan parameter kimia (BOD, nitrat, NH3), serta untuk data sekunder tentang sanitasi kandang ternak dan kualitas air sungai. Data dianalisis secara deskriptif dan spasial menggunakan klasifikasi risiko semi-kuantitatif berdasarkan melebihi standar kualitas nasional. 58% kandang ternak tidak memiliki sanitasi yang memadai. Kadar BOD mencapai 14 mg/L (2,33 kali lebih tinggi dari standar nasional), dan NH_3 mencapai 0,64 mg/L (32 kali lebih tinggi). Tidak satu pun sampel air rumah tangga yang memenuhi syarat untuk pengujian mikrobiologi total. Terdapat gradien peningkatan kontaminasi di daerah hulu (Pudak) dengan beban polusi sedang, daerah transisi (Pulung) dengan tingkat kontaminasi sedang akibat paparan hulu, dan hilir (Sooko) dengan kontaminasi tinggi. Pola kontaminasi menunjukkan gradien peningkatan risiko dari sumber limbah hulu ke hilir. Peningkatan sanitasi kandang ternak dan pengelolaan limbah ternak di daerah hulu perlu menjadi prioritas intervensi kesehatan lingkungan.

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1. Introduction

Environmental pollution from cattle farm waste has been identified as a public health challenge in various countries (Y. Wu, Li, & Fang, 2021), particularly in rural areas of low-and middle-income countries (Williams, von Stackelberg, Guerra Lopez, & Sanchez-Triana, 2021). Untreated cattle manure discharged directly into the environment may lead to microbiological and chemical contamination of surface water and groundwater (Alharthi et al., 2025). This condition increases exposure to microbiological and chemical contaminants, particularly among vulnerable groups such as women of reproductive age and children (Wulandari et al., 2024), who utilize local water sources for domestic needs (Begum, Ehsan, & Ehsan, 2022; Cameron, Chase, & Contreras Suarez, 2021). Such a condition shows that livestock is not only a local sanitation problem but also a matter requiring integrated investigation (Wang et al., 2023). Therefore, the need to understand contamination patterns across different regions is growing to plan more effective environmental health interventions.

Previous studies have shown that the relationship between livestock activities and decreased water quality. Contaminants such as *Escherichia coli*, *total coliform*, and *nitrates* were associated with an increased risk of waterborne diseases, including diarrhea and gastrointestinal infections (Li et al., 2022; Sharma, Rajan, & Nayak, 2023). In addition, exposure to contaminated water has been linked to adverse reproductive outcomes, including complications during pregnancy and an impact on fetal complications at birth (Singh, 2023). In developing countries, small-scale farming practices are generally located close to settlements without adequate sewage treatment systems (Heriyanti, Purwanto, Purnaweni, & Fariz, 2022). Discharging livestock waste directly into soil or water bodies may trigger the growth of pathogenic bacteria and increase the load of organic and nitrogenous pollutants (Herawati et al., 2024; Ibekwe et al., 2023). The impact of this pollution is often not limited to the surrounding area; it may also extend along hydrological flows, affecting water quality in areas farther from the source of the pollutant. There is no integrated spatial environmental assessment that limits a policy to identify high-risk environments and prioritize targeted sanitation interventions. In Indonesia, small-scale cattle farming has expanded around residential areas with limited sanitation management (Sifullah et al., 2024) and around residential neighborhoods with limited sanitation management (Cronin et al., 2017). Several studies in Indonesia reported a decline in household water quality with regard of both microbiological and chemical aspects (Coughlin et al., 2022; Daly & Harris, 2022; Larson et al., 2023). Therefore, further research is urgently needed to achieve a more comprehensive understanding of contamination pathways in livestock.

Ponorogo Regency is one of the areas with a high density of community cattle farms and river flows from upstream to downstream. Three main sub-districts (Pudak, Pulung, and Sooko) have concentrated on livestock activities that generate substantial waste, as evidenced by the number of farmer households and a large livestock population, namely Pudal (9,520 farmer households), Pulung (230 farmer households), and Sooko (150 farmer households). This condition is suspected to contribute to the decline in the quality of household water for drinking, cooking, and daily activities. These geographical characteristics provide an opportunity to do an initial assessment of the spatial distribution of contamination along the regional gradient. Previous studies in Indonesia generally still assessed livestock sanitation and household water quality separately. Consequently, the understanding of contamination pathways in the upstream and downstream hydrological systems is still limited, and the evidence of the integration of livestock sanitation and water contamination from the latter, confirmed by the laboratory with risk mapping, is still scarce (Dharmayanti et al., 2025; Nurul Arifiani & Rachmawati, 2024). In fact, the river system flows from upstream to downstream

(Safitri, D.N, 2024; Setyawan, Muhammad, & Hermawan, 2024). Spatial analysis is needed to describe contamination distribution patterns and to identify areas with higher exposure levels. This approach provides an important basis for more targeted and evidence-based environmental health policy planning. Based on the analysis, there is limited evidence in Indonesia of a single exploratory environmental assessment framework that simultaneously combines observations of livestock cattle pen sanitation, laboratory testing of household water quality, and mapping of environmental health risks. Therefore, this study aims to explore the spatial distribution of household water contamination associated with livestock waste and to identify environmental health risks along the upstream–downstream gradient in Ponorogo Regency to inform the prioritization of initial sanitation interventions.

2. Methods

This study was a preliminary case study using an exploratory-descriptive design and spatial analysis, not inferential statistics or population representations. It was conducted in March 2025 in Ponorogo Regency, East Java, Indonesia, in three districts: Pudak (upstream), Pulung (transitional), and Sooko (downstream). The three areas were selected because they have a high density of cattle ranches, diverse topography, dense populations, and water-use characteristics. In addition to primary data, this study also used secondary data obtained from related agencies, namely river water quality data (BOD, NH_3, nitrates) from the environmental agency, livestock density and population density data from Indonesia Statistical Body (Badan Pusat Statistik, BPS) and the Animal Husbandry Service, as well as disease indication data in women of reproductive age and children from the local health center. The study population comprised all households in the three districts.

The environmental focus was on household water sources of shallow wells, springs, and rivers that have the potential to be exposed to livestock waste. The study sample included 15 households, deliberately selected for their proximity to cattle pens and spatial position (upstream, transitional, and downstream). Fifteen samples (upstream = 5, transition = 5, downstream = 5) were selected using a purposive, exploratory environmental assessment approach. This design is not for statistical generalization but to identify early patterns of spatial distribution of contamination in hydrological gradient-based environmental systems. The sample selection was conducted in a stratified purposive manner based on upstream, middle, and downstream spatial positions and proximity to potential sources of contamination in livestock cages. One water sample was collected from each household, for a total of 15 water samples tested in the laboratory for chemical parameters (BOD, nitrate, and NH_3) and microbiological parameters (*total coliforms* and *Escherichia coli*). The water sample selection used a purposive sampling technique based on proximity to the cattle pen and spatial position. The samples were tested for the *total coliform* and *E. coli* (microbiology parameters), BOD, ammonia, and nitrates (chemical parameters).

Secondary data included in the study were data on the sanitary conditions of livestock pens, sewage disposal systems, and river water quality. The observed indicators consisted of sanitary conditions of livestock cages, river and household water quality, and regional spatial position, as the basis for environmental health risk classification. Laboratory testing was carried out for chemical parameters (BOD, nitrates, ammonia) and microbiological parameters (total coliform, *E. coli*), with reference to the Regulation of the Minister of Health No. 23/2021 (microbiological quality standard = 0 CFU/100 mL). Then, for the laboratory analysis method, the test followed the related National Standard (Standar Nasional Indonesia, SNI) using a pH meter, turbidimeter, spectrophotometer, BOD incubator, and the Most Likely Number (MPN) method for microbiological parameters. All of these tests were carried out in accordance with standard laboratory criteria at the Ponorogo Regional Health Laboratory. Risk levels were categorized descriptively, based on water-quality exceedances and spatial accumulation patterns, into moderate-, high-, and very high-risk areas. The laboratory results were compared with the national quality standards. The level of risk was classified semi-quantitatively based on the degree of standard exceedance and the region's position (high–very high). Spatial analysis was used to map the risk gradients: the distribution and gradient of water quality risks in the study area. The results of the spatial analysis were presented in the form of tables, drawings, and risk distribution maps. Ethical clearance was issued by the Institutional Research Ethics Commission of the University of Diponegoro, Semarang, No. 270/EA/KEPK-FKM/2025.

3. Results

The most common distribution of farmer households was Pudak District (520 families), followed by Pulung District (230 families), and Sooko District (150 families). The proportion of cattle pens that did not meet sanitation requirements remained high, especially in Pudak (58%), compared with Pulung (45%) and Sooko (40%). This practice was most common in the upstream areas (Pudak) and gradually decreased toward the transition areas (Pulung) and downstream (Sooko). This pattern indicates that direct waste disposal remained the dominant method of livestock waste management in the study area.

Table 1. Sanitary conditions of cattle sheds, well water quality, and scope of biodigester programs in three Ponorogo Regencies

Indicator	Pudak (Upstream)	Pulung (transition)	Sooko (Downstream)
Number of cattle farmer households	520 households	230 households	150 households
Pens not meeting sanitary standards	302 units (58.0%)	104 units (45.0%)	60 units (40.0%)
Waste disposal in cattle pens	The majority go directly to rivers/open land	Mix: open land and upstream	Upstream & local waste accumulation
Unqualified well water quality (percentage)	15.6%	12%	18%
Well water quality does not meet requirements (number of households)	81 households	28 households	27 households
Bio digester	There are, but limited	Limited project pilot	Almost no program
Number of units of bio digester	104 units (20.0%)	35 units (15.0%)	12 units (8.0%)
Households without a bio digester	416 households (80.0%)	195 households (85.0%)	138 households (92.0%)

The water quality of household wells indicated that 15.6% (81 households) of wells in Pudak, 12% (28 households) in Pulung, and 18% (27 households) in Sooko were unhealthy. The bio digester program had been introduced in Pudak, but coverage was still limited to less than 20% (104 units), while in Pulung it reached 15% (35 units), and in Sooko it was less than 10% (12 units). Thus, most households lacked facilities for treating livestock waste (Table 1).

Table 2. River water quality in the research area

Parameter	Location/River Point	Measurement Results	Quality Standards *	Status
BOD (mg/L)	Some river points (Pudak & Sooko)	14 mg/L	6 mg/L	Exceeded standards (2.33 times higher)
NH_3 (Ammonia) (mg/L)	Keang River, Sooko	0.64 mg/L	0.02 mg/L	Exceeded standards (32 times higher)
Nitrate (mg/L)	Pudak & Sooko (some points)	> Quality Standards	10 mg/L	Inappropriate
Total Coliform (CFU/100 mL)	Pudak rivers	8,000 CFU/100 mL	5,000 CFU/100 mL	Exceeded standards (1.6× higher)
Coliform Feces (CFU/100 mL)	Keang rivers	2,500 CFU/100 mL	1,000 CFU/100 mL	Exceeded standards (2.5× higher)

** Regulation of the Minister of Health Number 2 of 2023*

River water quality measurements show that several parameters exceeded national quality standards. The BOD value reached 14 mg/L, which was about 2.33 times the threshold (6 mg/L). The ammonia (NH_3) level in the Keang River, Sooko, was recorded at 0.64 mg/L, which was 32 times the standard limit (0.02 mg/L). Microbiological parameters also show elevated levels: total coliforms at 8,000 CFU/100 mL and fecal coliforms at 2,500 CFU/100 mL. These findings indicated the presence of organic and microbiological pollution loads on water bodies (Table 2).

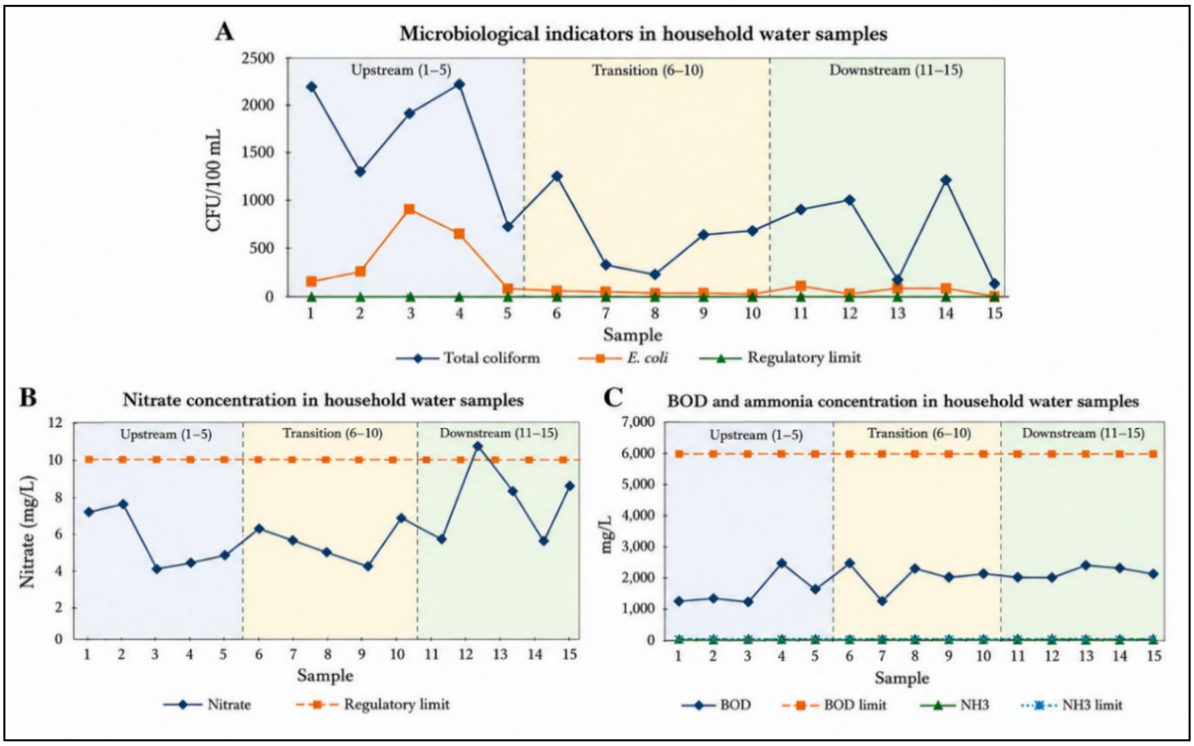

Figure 1. *Coliform* and *E coli*, BOD, Nitrate, and NH_3 concentrations in household water samples compared to regulations

Table 3. Epidemiological risk map based on cattle farm area in Ponorogo, Indonesia

Region	Waste Flow Position	Topography Characteristic & Population Density	Number of Cattle Farms	Main Water Sources	Sanitation & Environmental conditions	Risk of Water Pollution	Health Risk Level*
Pudak	Upstream	959 MDL; Density 115 inhabitants/km^2	7.815	Mountain springs, PAMSIMAS & bore wells	58% of cattle pens are non-compliant; direct sewage disposal into the river	High (*E. coli*, nitrate)	High
Pulung	Transition	356–746 MDL; Density 381 inhabitants/km^2	2.255	Mountain springs, PAMSIMAS & bore wells	Mixed sanitation; Exposed to upstream waste streams	Medium–High (*E. coli*)	Medium –High
Sooko	Downstream	304–516 MDL; Medium density	254	Mountain springs, PAMSIMAS & bore wells	Accumulation of upstream waste exposure; Deteriorating water quality	Very High (*E. coli*, BOD, NH_3)	Very high

**: Risk classification is determined based on the number of parameters that exceed the quality standard, the level of exceedance, the sanitary conditions of the cage, and the spatial position of the area in the upstream-downstream system.*

All tested household water samples (n=15) were positive for total coliforms and did not meet the microbiological requirements for clean water. The total coliform concentration ranged from 127–2,281 CFU/100 mL, and E. coli concentration ranged from 0 – 890 CFU/100 mL, while the standard of quality was 0 CFU/100 mL. Therefore, the entire sample was categorized as non-compliant (100%). The distribution of coliform concentrations is shown in Figure 1.

The Pudak area is categorized as high risk due to the large density of livestock and the high proportion of inadequate cattle pen sanitation. Pulung serves as a transition zone with mixed exposure. The Sooko region shows the highest accumulation of pollutants and is classified as very high risk. The risk classification is based on the degree of exceedance of water quality standards and the region's spatial position (Table 3).

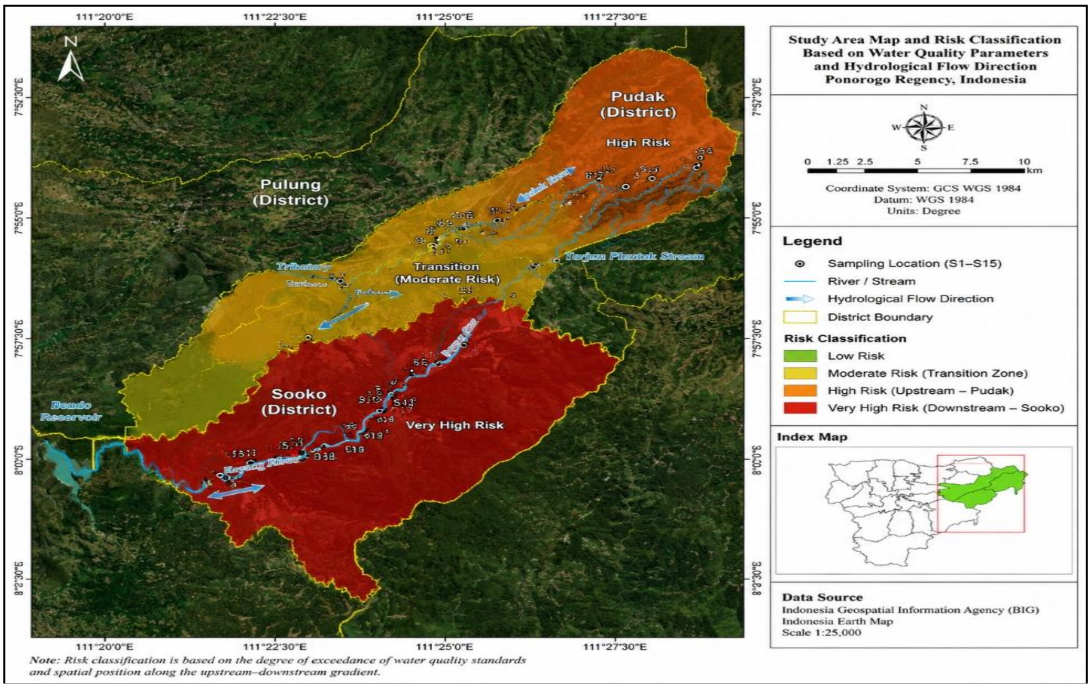

Figure 2. Mapping upstream-downstream risk classification based on water contamination

4. Discussion

This study describes a consistent spatial pattern between the existence of cattle farms, cattle pen sanitation conditions, and the distribution of water contamination at the household level. Upstream areas (Pudak) with high livestock density and a high proportion of cattle pens with sanitation are the main sources of pollutant loads. This condition was reflected in the declines of river water quality in transition and downstream areas, as well as in the discovery of microbiological contamination in household well water (Tokatlı, Varol, & Uğurluoğlu, 2024). The gradient pattern observed in this study indicates the accumulation of pollutants throughout the hydrological flow.

The findings indicating exceeding quality standards for BOD and ammonia parameters indicate a high burden of organic and nitrogen pollution, while all coliform-positive household water samples indicate fecal contamination (Alkhalidi, Al-Nasser, & Al-Sarawi, 2022; Ouattara et al., 2023; Some et al., 2021). These findings are in line with studies in several developing countries that small-scale farming activities without adequate waste management are associated with a decline in domestic water quality (Hridoy, Neogi, Ujjaman, & Hasan, 2025; Sifullah et al., 2024). Although this study is descriptive and not intended to test causal relationships, the consistency of the observed spatial patterns provides a basis for considering region-based sanitation interventions. Contaminated household water may increase community exposure to pathogens (X. Wu, Nawaz, Li, & Zhang, 2024; de

Lambert, Walsh, Scher, Firnstahl, & Borchardt, 2021), especially for vulnerable groups, such as children and women of reproductive age, who interact more frequently with water for domestic activities. Some previous studies reported that exposure to polluted water in rural environments was associated with an increased incidence of waterborne diseases (Asakura et al., 2023; Bindra, Ravindra, Chanana, & Mor, 2021; Kang, Lee, & Cho, 2020). These results were also reported by Asakura et al (2023), who found that rural communities living near livestock facilities have a higher risk of developing waterborne diseases such as diarrhea, gastroenteritis, and typhoid fever (Asakura et al., 2023). In low- and middle-income countries, the risk increases due to limited clean water and sanitation infrastructure (Foster et al., 2021; Maysarah et al., 2020; Zavala, King, Sawadogo-Lewis, & Roberton, 2021). The findings in this study, while not directly assessing clinical outcomes, indicate the need to address the protection needs of vulnerable groups by providing clean water and improved environmental sanitation (Maneeprakorn et al., 2024; Akintunde, Ozebo, & Oyedele, 2022).

An integrative approach that combines cattle pen sanitation observation, water-quality laboratory testing, and spatial risk mapping provides a more comprehensive picture of contamination pathways than a single approach. The identification of upstream areas as potential sources of pollutants suggests that measures such as improved cage sanitation, treatment of livestock waste, and expanded use of biodigesters can be prioritized. In addition, public education about household water treatment and shallow well protection is also needed to reduce exposure. The results of risk mapping in this study can be used as a basis for determining the priority of environmental health interventions in stages, focusing on areas with the highest levels of exceedance of quality standards. Area-based approaches are expected to be more effective than generalized interventions that do not account for the spatial distribution of pollution.

In environmental water quality studies, water quality degradation is influenced not only by livestock activities but also by environmental physical conditions (such as well conditions and well depth) and by the distance between water sources and polluting sources (such as livestock pens and septic tanks), which may contribute significantly to variations in groundwater quality. In addition, local hydrological characteristics, soil type, and surface water flow patterns also affect the likelihood of contaminant infiltration into household water sources. In addition, other anthropogenic activities such as domestic waste disposal, rainwater runoff, and land use around the research area also have the potential to be additional sources of pollution. Thus, although this study shows a consistent spatial pattern between farm density and increased pollutant levels along the upstream–downstream gradient, the interpretation of the results still needs to account of other factors that may contribute to these conditions. However, based on the consistency of the pattern of increasing pollutant loads in areas with higher livestock intensity, as well as the regularity of the spatial gradient that follows the direction of hydrological flows, livestock activity can still be identified as the dominant factor in the context of this study area.

This study was an initial assessment with a limited number of laboratory samples and data collected over time, so the results were descriptive and not intended for generalization to the population. The parameters analyzed were primarily basic bacteriological and chemical indicators, so the possibility of other contaminants could not be assessed. In addition, the study did not evaluate clinical data on the disease. Follow-up studies with a wider sample, longitudinal design, and more comprehensive testing parameters are needed to strengthen the evidence and support the formulation of environmental health policies.

5. Conclusions

This study demonstrates a clear spatial gradient of water contamination associated with livestock waste, with pollution levels increasing from upstream to downstream areas. High livestock density and inadequate sanitation practices in upstream areas are identified as key drivers of environmental contamination that subsequently accumulates along hydrological pathways. The consistent presence of microbiological contamination across all household water samples underscores a significant public health concern, particularly for communities relying on untreated local water sources.

These findings emphasize that upstream waste management plays a critical role in protecting downstream water quality. Therefore, environmental health interventions should prioritize improvements in cattle waste sanitation, proper livestock waste management, and the expansion of biodigester programs, especially in upstream areas. In parallel, community-based strategies such as household water treatment, safe water storage, and the protection of water sources are essential for reducing direct exposure.

Overall, this study provides an initial but important contribution to understanding the spatial dynamics of livestock-related water contamination in rural Indonesia and offers a practical foundation for targeted and area-based environmental health interventions.

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