EAM
Environmental and Materials
EAM 3(1): 31–52
ISSN 3025-0277

Uncovering the spatial link between environmental risks, diarrhea incidence, and health service accessibility

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Received Date: June 6, 2025 Revised Date: June 30, 2025 Accepted Date: June 30, 2025

ABSTRACT
Background: This study investigates spatial disparities between healthcare capacity, hospital accessibility, and environmental risk of diarrhea in West Java Province. Using a combination of Geographic Information System (GIS), network-based travel-time modeling, Principal Component Analysis (PCA), and clustering, the research identifies mismatches high-risk areas and low-access healthcare infrastructure. Spatial overlay reveals that districts such as Tasikmalaya, Garut, and Cianjur experience dual vulnerabilities—limited healthcare reach and elevated environmental risk indicators. **Methods:** PCA was used to reduce multicollinearity among six environmental and socioeconomic variables, including access to sanitation, drinking water, latrine type, and poverty level. After excluding three extreme outliers, 24 districts were clustered using PCA-derived composite scores. The clusters were overlaid with hospital accessibility maps from service area analyses (≤30 and 31–60 minutes). PCA explained 80.4% of the total variance. **Findings:** The results show that 3 out of 27 districts, such as Tasikmalaya, Garut, and Cianjur; exhibited critically low hospital bed ratios, and over 50% of their population is located outside the 30-minute service area of a hospital. PCA-based clustering revealed four spatial risk typologies, with Cluster 4 (extreme outliers) representing the highest composite risk from poor sanitation, communal latrines, and high poverty. These findings underscore a spatial mismatch between environmental vulnerability and healthcare accessibility. **Conclusion:** Integrated spatial planning is urgently needed in high-risk, low-access areas, combining infrastructure expansion with digital health solutions. **Novelty/Originality of this article:** This study introduces a spatial typology of diarrhea risk in West Java by integrating PCA and GIS-based accessibility, and aligns its recommendations with Indonesia's national health policy frameworks (RPJMN 2025–2029 and PP No. 28/2024) to support data-driven, equitable public health interventions.

KEYWORDS: diarrhea; environmental risk; GIS; healthcare accessibility; spatial disparities.

1. Introduction

Diarrheal disease remains one of the leading causes of morbidity and mortality in developing countries. According to the Global Burden of Disease Study 2021, there were over 467 million new cases of diarrhea worldwide in 2021, making it the second most common disease after upper respiratory tract infections (Zhao et al., 2025). This issue is strongly associated with environmental conditions, such as limited access to clean water, inadequate sanitation facilities, and poor hygiene practices (Alum et al., 2024; WHO, 2023). Approximately 88% of global diarrhea cases are attributable to poor water, sanitation, and hygiene (WASH) practices, with the most significant impact occurring in rural and

Cite This Article:
Listyono, G. M., Oinike, A., & Hambali, D. (2025). Uncovering the spatial link between environmental risks, diarrhea incidence, and health service accessibility. *Environmental and Materials, 3*(1), 31-52. https://doi.org/10.61511/eam.v3i1.2025.1946

impoverished communities (Alum et al., 2024). Therefore, improving water quality and sanitation is a key strategy in controlling diarrheal diseases as well as achieving SDG 3 and SDG 6.

Inequitable access to healthcare services remains a fundamental challenge in developing countries. Although there has been an increase in the coverage of health interventions over the past two decades (Victora et al., 2017), as well as a global rise in the UHC service coverage index from 45 to 68 between 2000 and 2021 (WHO, 2025). The equitable distribution of their benefits has yet to be fully achieved. An analysis of 64 low- and middle-income countries revealed that poor and rural populations, despite experiencing relatively faster gains in coverage, continue to face structural barriers in accessing essential services (Victora et al., 2017). This issue is further exacerbated by inadequate health infrastructure, shortages of medical personnel, and high out-of-pocket costs, particularly in remote areas (Pauley, 2023). Achieving equitable and inclusive Universal Health Coverage requires a comprehensive strategy that specifically targets vulnerable groups through spatially-based interventions and justice-oriented policies.

West Java is the most populous province in Indonesia, with a total population of 50,489,208 people (Badan Pusat Statistik, 2024c). In addition, the province ranks second highest nationally in terms of the number of people living in poverty, reaching 3,848,670 individuals (7.46%) in 2024 (Badan Pusat Statistik, 2025), has the highest number of divorce cases (102,280 cases) in 2023 (Badan Pusat Statistik, 2024a), and recorded the highest number of school dropouts from public schools (5,080 cases) in 2023 (The Center for Data and Information Technology, 2024). The province faces serious challenges in achieving equitable access to basic services, including environmental quality and healthcare facilities (Barwanto & Ramadhan, 2024; Badan Pusat Statistik, 2024c). This spatial disparity is reflected in the uneven distribution of infrastructure, such as road length, number of schools, and availability of public facilities, which remain low in many districts and municipalities (Noviyanti et al., 2020; Wardhana et al., 2020). Several areas—such as Garut, Tasikmalaya, Cianjur, and Ciamis—have even been classified as regions with poor access to basic services and limited health infrastructure, including hospital bed ratios that fall significantly below the ideal standard (Aprianoor & Muktiali, 2015; Noviyanti et al., 2020). These disparities further exacerbate the vulnerability of southern West Java to demographic pressures and worsening environmental health issues (Barwanto & Ramadhan, 2024; Kondolele et al., 2023).

To address these issues, the government has implemented various interventions, such as increasing the coverage of diarrhea treatment services for children under five—targeting 20% of estimated cases in this age group and 10% of cases across all age groups—the launch of the LINTAS Diarrhea Program (*Lima Langkah Tuntaskan Diare* or Five Steps to Eliminate Diarrhea), and the establishment of a target for 100% hospital accreditation (Dinas Kesehatan Provinsi Jawa Barat, 2024). However, challenges remain in the implementation of these efforts, including the need for comprehensive planning to ensure the equitable distribution of physical facilities, as well as improvements in the quality and quantity of human resources (Handayani et al., 2019), and the provision of adequate technology and funding (Komar et al., 2022). The variations in facility availability, disease burden, topography, and road conditions across districts and cities in West Java Province highlight the need for a sustainable and inclusive approach to ensure that all population groups have equal access to healthcare services (Sarilita et al., 2023).

Therefore, a spatial approach is not only useful for analyzing accessibility but is also crucial in supporting regional planning and the equitable, sustainable distribution of healthcare facilities. Law No. 26 of 2007 concerning Spatial Planning emphasizes the importance of legal certainty, cross-regional integration, and equity in spatial use as core principles of spatial planning (Huda & Najicha, 2023). In the context of healthcare, this principle implies that the provision of health facilities must be based on objective and equitable assessments of community needs. A study in Sukoharjo Regency found that hospitals tend to be concentrated in urban centers, leaving southern areas spatially vulnerable (Pratama, 2022). Similarly, research in Bojonegoro Regency revealed that only

6% of the region lies within a 3,000-meter radius of a hospital facility, well below the ideal standard outlined in Indonesia National Standard number 03-1733-2004 (Mas'udah, 2023). These disparities underscore the importance of integrating Geographic Information Systems (GIS) into spatial planning to scientifically identify priority facility locations, minimize political bias in budget allocation, and uphold the principle of spatial justice in healthcare service systems.

In supporting evidence-based spatial planning, the availability of accurate, open, and validated spatial data serves as a critical foundation for inclusive and well-targeted decision-making. One commonly used source of participatory spatial data is Volunteered Geographic Information (VGI), such as OpenStreetMap, which was first conceptualized by (Goodchild, 2007) as user-generated geospatial content voluntarily contributed by individuals through web-based platforms. A study by Haningrum et al. (2022) demonstrated that the spatial quality of OpenStreetMap in Semarang City—evaluated using ISO 19157:2013 standards—achieved a map grade index of 3.07 and was categorized as "excellent" for spatial planning purposes, proving that participatory data can be reliable when assessed systematically. On the other hand, research by Boeing et al. (2022) emphasized that open data and open-source tools can be effectively used to develop spatial indicators that reflect inequalities in access to public transportation, green spaces, and healthcare services at the urban scale. However, in developing countries, spatial data quality and completeness often remain uneven, making local validation and community engagement crucial for improving data accuracy. Through participatory approaches and the use of validated open data, healthcare service planning can become more equitable, transparent, and evidence-based.

In addition, access to healthcare services is not solely determined by the availability of facilities but also by the population's physical ability to reach them (Chowdhury & Ravi, 2022). Infrastructure disparities in rural and border areas of West Java—such as damaged roads and limited public transportation—have been shown to hinder mobility and access to healthcare services (Redaksi Teras Jabar, 2024). Data from 2023 indicate that there are still districts where less than 40% of roads are paved, which significantly impacts travel time to healthcare facilities, as evidenced by studies conducted by Putri et al. (2021) and Yudono et al. (2023). These findings highlight the heightened vulnerability of communities in underdeveloped areas to delays in receiving medical treatment, particularly during seasonal diarrhea outbreaks, which in some cases in West Java have been declared Extraordinary Events (KLB) and have resulted in fatalities (Dinas Kesehatan Provinsi Jawa Barat, 2024).

Several studies have shown that the risk of diarrhea incidence is strongly influenced by environmental factors such as sanitation quality, access to clean water, and the socioeconomic conditions of the population. In coastal and densely urbanized areas, poor sanitation—particularly in public latrines and waste disposal systems—has been proven to increase vulnerability to diarrhea (Nabila & Hendrawan, 2025; Prakoso, 2020). Although studies using national-level data indicate that sanitation and access to clean water are not always statistically significant in urban contexts, socio-demographic variables such as parental education, child's age, and household income show strong correlations with diarrhea prevalence (Fahira et al., 2021). Moreover, the decline in water quality due to domestic waste in densely populated settlements exacerbates exposure to pathogens, while the implementation of behavior-based interventions, such as the Community-Based Total Sanitation (STBM) program, has proven effective in reducing diarrhea incidence, especially among vulnerable groups such as children under five (Hafwi et al., 2023).

Nevertheless, the complex interrelationships among environmental variables often result in multicollinearity, making it difficult for researchers to directly identify the dominant risk factors. To address this challenge, statistical approaches such as Principal Component Analysis (PCA) can be employed to reduce dimensionality and construct groups of variables that represent a more interpretable risk structure. A study by Mamouei et al. (2022) demonstrated that a similar approach, namely Sparse PCA, was effective in clustering highly correlated environmental indicators and highlighting dominant variables—such as noise pollution—that were significantly associated with mortality risk. This approach is highly relevant in the context of diarrhea risk assessment, where factors such as sanitation, access to clean water, and poverty often overlap and are difficult to disentangle through conventional statistical methods.

Although several previous studies have employed spatial approaches to map the distribution of diarrhea cases and identify environmental factors (Muhajjar et al., 2016; Pertiwi, 2019), the comprehensive integration between spatial analysis of healthcare access and environmental risk clustering remains limited, particularly in densely populated regions such as West Java. A study by Husna & Purwandari (2023) in West Java focused solely on mapping diarrhea risk factors based on socioeconomic and sanitation characteristics using K-Means Clustering, without incorporating the spatial dimension of healthcare accessibility. By integrating Geographic Information Systems (GIS), Principal Component Analysis (PCA), and spatial travel-time analysis, this study offers a novel contribution in identifying priority intervention areas based on the complexity of environmental risk and service accessibility. This approach supports evidence-based decision-making that is more spatially just, particularly in health infrastructure planning within regions characterized by challenging topography and pronounced social inequalities.

2. Methods

This study employs a quantitative approach by integrating spatial analysis with statistical modeling to examine the relationship between environmental and non-environmental risk factors and the incidence of diarrhea, as well as to analyze the accessibility of healthcare facilities in West Java Province. The study combines Geographic Information System (GIS) techniques, Principal Component Analysis (PCA), travel-time modeling, and cluster analysis to map the spatial patterns of health risks and healthcare service disparities.

2.1 Research location

The study was conducted in West Java Province, Indonesia. Geographically, West Java is bordered by the Java Sea and the Special Capital Region of Jakarta to the north, Central Java Province to the east, the Indian Ocean to the south, and Banten Province to the west. The province is characterized by complex natural features and diverse geological structures. Mountainous areas dominate the central and southern regions, while lowland areas are found in the northern part. West Java consists of 27 regencies and cities, comprising 18 regencies and 9 cities.

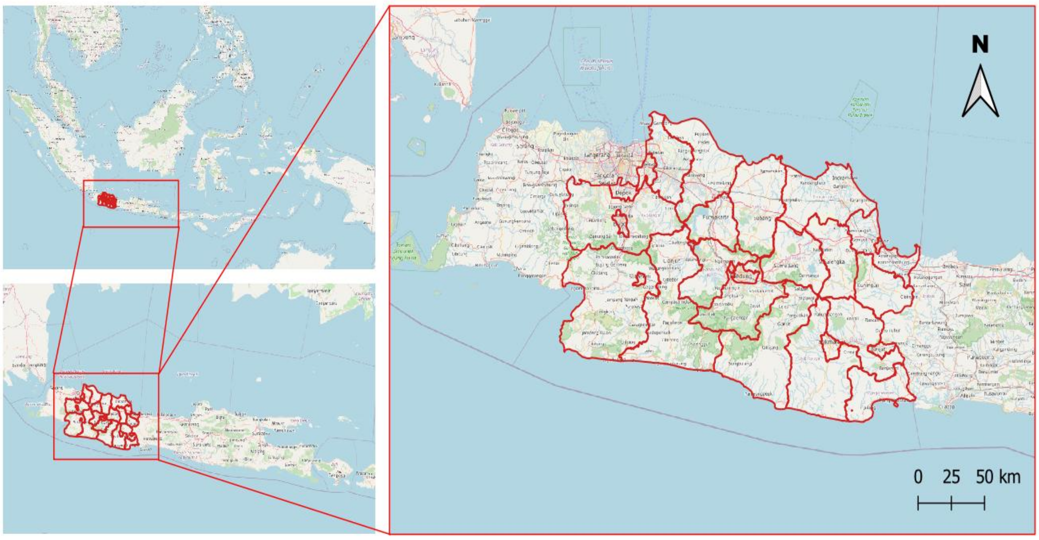

Fig. 1. Research location

The province has a complex topography, with lowlands in the north and mountainous regions in the south and center. It also has the highest population density in Indonesia (excluding Jakarta), reaching 1,370.38 people per km^2, and has experienced a high prevalence of communicable diseases such as tuberculosis (TB), HIV/AIDS, dengue fever (DF), and diarrhea over the past decade (Badan Pusat Statistik, 2024b). The diversity in geographical conditions and the unequal distribution of hospitals make this region particularly relevant for analyzing healthcare facility accessibility. The study area map is presented in Figure 1.

2.2 Scope of accessibility

Early approaches to healthcare accessibility analysis in the 1970s–1980s focused on the functional relationship between communities and health facilities, emphasizing the alignment between population needs and the availability of healthcare resources. During the 1990s–2000s, the concept of accessibility evolved to incorporate financial, geographic, and service quality dimensions, highlighting how individuals seek and utilize healthcare services. Since the 2010s, accessibility approaches have become more holistic and comprehensive, encompassing both demand and supply-side factors, including geographic, social, and cultural barriers, while also emphasizing the process from need identification to service utilization (Dwi et al., 2016). In line with this evolving definition, a healthcare accessibility index is established in this study, consisting of three key aspects: supply (availability of facilities and healthcare personnel), barriers (geographic, financial, and insurance-related constraints), and demand (the utilization rate of outpatient and inpatient services at various healthcare facilities). In this study, the supply index is represented by the ratio of hospital beds to population and the number of public and private hospitals; the barrier index is represented by travel time to the nearest hospital; and the demand index is reflected by outpatient service coverage at hospitals. The initial analysis involves mapping the distribution of hospital bed availability ratios and disease incidence per district/city. These areas serve as the basis for justifying priority locations for travel time-based accessibility analysis using the network analyst method (McGrail & Humphreys, 2009).

2.3 Data and variable

Table 1 presents the primary data sources used in this study, which include both spatial and statistical datasets. The spatial data comprise administrative boundaries from InaGeoportal (BIG), road networks from OpenStreetMap, and hospital locations obtained via Google Earth Pro. Statistical data on population, poverty, health indicators, and sanitation were primarily sourced from the West Java in Figures 2024, West Java Provincial Health Profile 2023, and the West Java Statistics Bureau (BPS). Key variables include the number of hospital beds, population per district/city, incidence of diarrhea, and access to drinking water and sanitation facilities that categorized into private, shared, and communal or no toilet access. These data sources were compiled and validated to support the spatial analysis of healthcare accessibility and environmental health risk factors across West Java.

Table 1. Data sources used in the study

No	Data description	Data source
1	Number of hospital beds per district/city	West Java Provincial Health Profile, 2023
2	Population per district/city	West Java Statistics Bureau (BPS)
3	Road Network	Open Street Map
4	Disease cases per district/city	West Java Statistics Bureau (BPS)
5	Administrative boundaries	Inageoportal – Geospatial Information Agency (BIG)
6	Hospital locations	Google Earth Pro
7	Number of diarrhea cases	West Java Provincial Health Profile, 2023
8	Access to improved drinking water	Provinsi Jawa Barat dalam Angka 2024
9	Access to improved sanitation	West Java in Figures, 2024

10	Private toilet facilities	West Java in Figures, 2024
11	Shared toilet facilities	West Java in Figures, 2024
12	Communal/no toilet facilities	West Java in Figures, 2024
13	Number of people living in poverty	West Java in Figures, 2024

2.4 Data preprocessing and analysis

All spatial data were converted to the World Geodetic System 1984 (WGS 84)/ Universal Transverse Mercator (UTM) Zone 48S coordinate system, which is appropriate for the geographical extent of West Java and allows for accurate area and distance calculations within a projected metric system (Snyder, 1987). Vector data for administrative boundaries were obtained from the Geospatial Information Agency (BIG) and the Central Statistics Agency (BPS), while spatial data for hospitals were acquired by plotting coordinate points using Google Earth Pro. Road network analysis was performed using the Road Graph and OpenRouteService Tools plugins in QGIS. The average travel speed used for estimating travel time was set at 40 km/h for four-wheeled vehicles. Capacity and accessibility analyses were conducted based on the ratio of the number of hospital beds to the population. The WHO standard (1:1,000) was used as the reference for classifying four levels of capacity: adequate, slightly inadequate, inadequate, and severely inadequate. For accessibility, service area analysis was performed based on travel time using the network analysis method (Arief et al., 2023). Travel time categories were defined as follows: accessible (≤30 minutes), moderately accessible (31–60 minutes), and poorly accessible (>60 minutes).

A study conducted by Khairunnisa et al. (2020) using a systematic review approach identified several variables as risk factors contributing to the incidence of diarrhea among infants and young children. These factors include handwashing behavior, availability of sanitation facilities (latrines), access to clean water, family socioeconomic status, housing density, exclusive breastfeeding practices, child nutritional status, vitamin supplementation, parenting patterns, and the quality of healthcare services. Meanwhile, a study by Jannah et al. (2023) also highlighted several risk factors for diarrhea among young children, including lack of exclusive breastfeeding, incomplete immunization, poor handwashing habits, low-quality water sources, low maternal education, and unfavorable socioeconomic conditions. Based on these findings, the present study examines key risk variables consisting of the following indicators: access to improved sanitation, access to improved drinking water, availability of private toilet facilities, shared toilet facilities, communal/no toilet facilities, and the proportion of the population living in poverty.

The analysis of diarrhea risk factors was conducted through statistical testing of each variable to evaluate their correlational relationships, followed by cluster analysis to group districts and cities in West Java Province based on similar risk patterns (Husna & Purwandari, 2023). In cases where multicollinearity was identified among the variables, Principal Component Analysis (PCA) was applied as an appropriate statistical solution. PCA was selected for its ability to address violations of the multicollinearity assumption without reducing the number of original variables, thereby preserving the full information contained within each variable. Prior to conducting PCA, the entire dataset was normalized to ensure balanced data distribution, and extreme outliers were detected. If outliers were found, they were removed to avoid distortion of the dataset's variance structure.

The next step involved calculating eigenvalues obtained from the PCA to generate new variables by multiplying the eigenvalues with the previously normalized dataset. The new dataset resulting from this PCA transformation was then re-evaluated statistically to ensure that the newly formed variables were free from multicollinearity. Once statistical validity was confirmed, cluster analysis was applied to identify regional groupings based on similar patterns of transformed risk factors. All analytical procedures—including statistical testing, PCA implementation, and spatial clustering—were conducted using data analysis software such as R Studio or Google Collaboratory with the Python programming language.

The methodological framework in this study was designed to provide a comprehensive spatial overview of the interrelationships between environmental risk factors, disparities in healthcare facility capacity, and hospital accessibility in West Java Province. By integrating hospital bed ratio analysis, travel-time modeling using GIS, and multivariate statistical approaches based on Principal Component Analysis (PCA) and clustering, this study aims to objectively identify highly vulnerable areas. The analytical procedures included spatial data validation, initial statistical testing, dimensionality reduction, and the formation of regional clusters based on dominant risk patterns. The findings from each of these stages not only support evidence-based decision-making but also serve as a foundation for advocating equitable and targeted interventions in regional healthcare systems. The complete results of these analyses are presented and discussed in the following Results and Discussion section.

3. Results and Discussion

3.1 Healthcare service capacity and diarrhea case burden

A spatial analysis of hospital bed distribution and population per subdistrict produced a map of the hospital service capacity ratio to population in West Java Province (Figure 2). These findings contribute to identifying disparities in healthcare service capacity as one of the key dimensions of vulnerability to environmentally-related diseases. The map reveals that most areas have not yet met the ideal standard recommended by the World Health Organization (WHO), which suggests the availability of one hospital bed for every 1,000 inhabitants. In this map, the regions are classified into four categories: the adequate category (1:266–1:1,000), which meets or closely approaches the WHO standard, followed by slightly inadequate to severely inadequate categories, with ratios reaching up to 1:5,997, indicating critically insufficient hospital bed capacity.

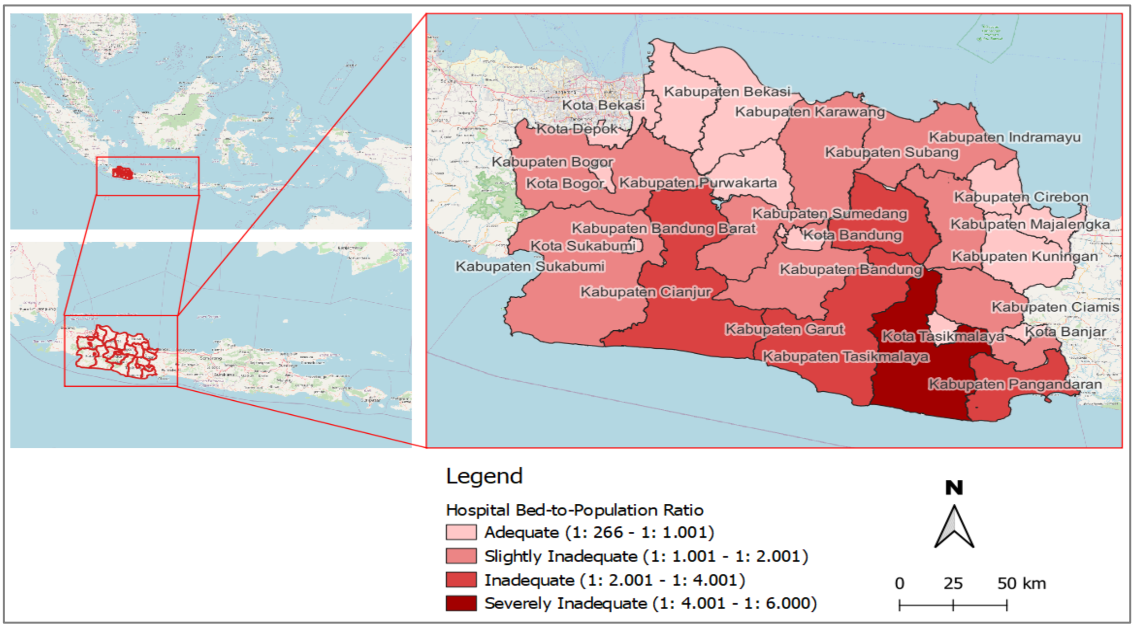

Fig. 2. Map of bed-to-population ratio distribution per subdistrict in West Java Province

Figure 2 illustrates the distribution of the hospital bed-to-population ratio at the subdistrict level in West Java Province. Visually, it is evident that many southern regions—such as Tasikmalaya, Cianjur, Garut, Pangandaran, and Sumedang Regencies—fall into the severely inadequate category, indicating a hospital bed ratio far below the minimum threshold set by the WHO (1:1,000). This disparity presents a significant risk of bottlenecks in the healthcare system, particularly during periods of high case burden, such as natural disasters or outbreaks of environmentally-related infectious diseases like diarrhea.

In the context of diarrhea endemic in West Java, limited hospital service capacity significantly affects the healthcare system's response capability, particularly during seasons with heightened incidence, such as the rainy season (Nuha et al., 2022). The spatial distribution of diarrhea cases in 2023, as presented in Figure 3a, shows a significant spatial correlation with areas that exhibit low healthcare capacity. This is further supported by data on the coverage of treated diarrhea cases during the 2020–2023 period (Figure 3b), which illustrates a decline in service accessibility during the pandemic, followed by a relative improvement in 2023. An editorial in The Lancet Public Health (2022) noted that the COVID-19 pandemic led many countries to experience disruptions in the provision of non-COVID health services, including for diarrhea, due to a shift in healthcare system priorities.

Furthermore, spatial analysis in Figures 2 and 3b indicates that southern regions of West Java consistently exhibit lower healthcare service capacity compared to northern areas such as Bekasi City and Regency, Karawang, Purwakarta, and Cirebon. This pattern reinforces the notion that disparities in the distribution of health infrastructure are influenced not only by demographic factors and service demand but also by biophysical elements such as morphology and spatial connectivity.

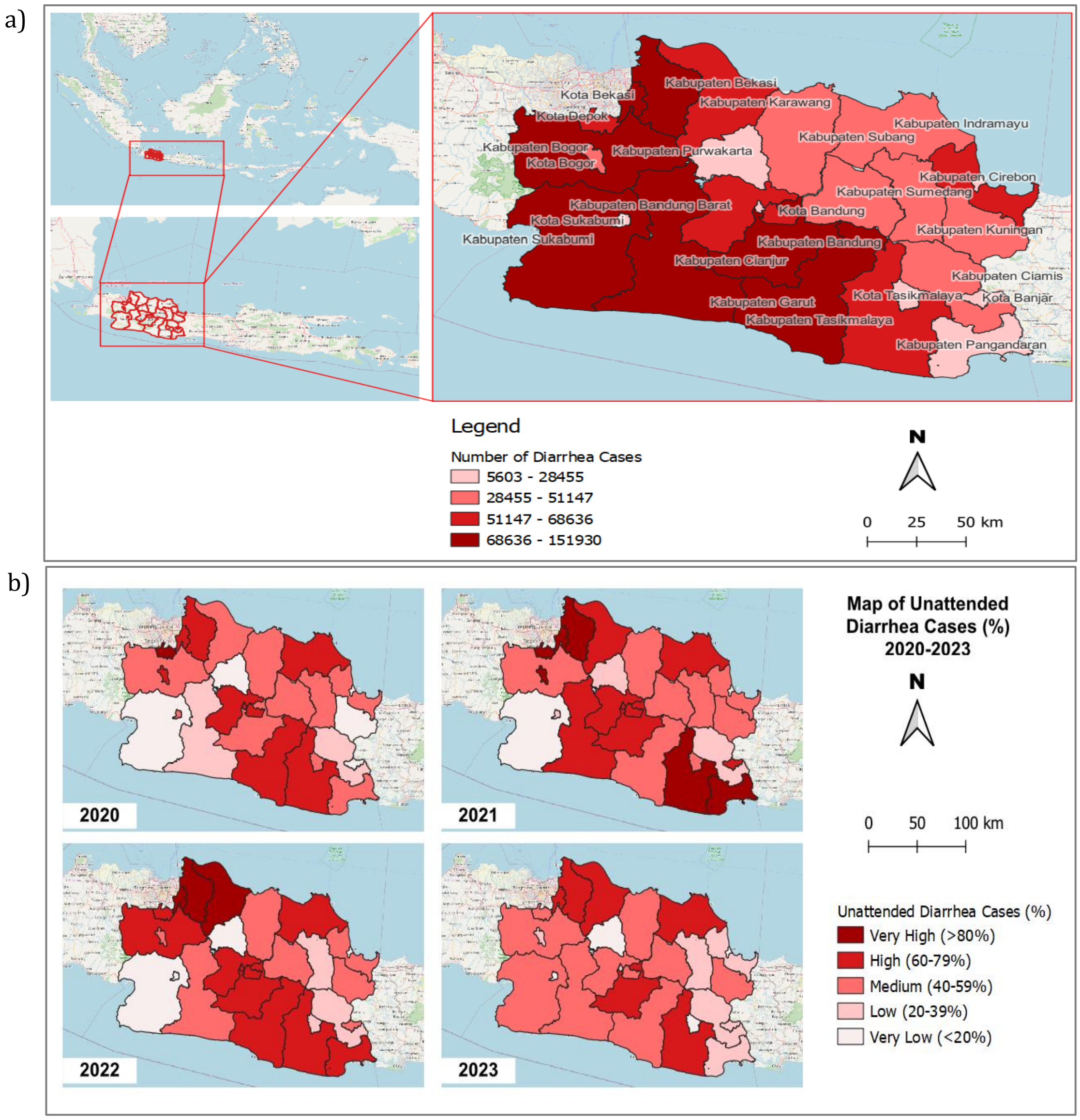

Fig. 3 (a) Distribution of diarrhea cases in districts/cities of West Java Province in 2023; (b) Spatio-temporal distribution of the ratio between unattended and total diarrhea cases in West Java Province, 2023

According to physiographic data from the West Java Environmental Agency (2025), areas that are geographically less accessible to hospital services are predominantly located within Structural Hills, Structural Mountains, Karst Hills, and volcanic zones. This aligns with the classical physiographic classification by Van Bemmelen (1949), which identifies the southern region of West Java as part of the Southern Mountain Zone and the Central Java Depression. For instance, the morphology of Tasikmalaya Regency is dominated by a complex of old and young volcanic formations such as Mount Galunggung, which has produced enclosed relief features like the Sepuluh Ribu Hills. Similarly, Garut and Cianjur possess depressed topographies surrounded by high mountains, which significantly increase spatial barriers to accessing public services.

These findings underscore the importance of considering physical environmental conditions in the provision of healthcare infrastructure. A study by Saputra et al. (2022) revealed that villages in the mountainous areas of Central Java with geographical constraints also experience disparities in the development of public facilities. A similar situation can be observed in West Java, where unequal road infrastructure further impedes mobility and access to healthcare in hilly regions (Siswantoro, 2024). The ecological implications of such topographic conditions place local communities in a state of double vulnerability, both medically and environmentally.

As a follow-up, several areas may be designated as priorities for the development of environmentally and spatially informed healthcare infrastructure. These efforts include improving the quantity and quality of health facilities (hospitals, community health centers, and referral units), providing adequate medical personnel, and strengthening healthcare financing for vulnerable populations. The commitment of the Tasikmalaya Regency Government, for instance, to build four new hospitals and establish a mobile service task force, represents a concrete step that must be closely monitored by cross-sectoral actors, including academic institutions, to ensure the effectiveness of interventions and the sustainability of programs within the framework of inclusive and responsive environmental development.

3.2 Hospital accessibility conditions in three priority districts

Based on the spatial mapping of diarrhea case numbers and the ratio of hospital beds to population, three districts in West Java were identified as priority areas for further analysis of healthcare accessibility: Tasikmalaya Regency, Garut Regency, and Cianjur Regency. These three districts exhibit critically low hospital bed availability, with all having ratios exceeding 1:2,000, alongside high absolute numbers of diarrhea cases. This combination places them in a critical position in terms of both service capacity and accessibility (Table 2).

Table 2. Hospital bed availability ratio per population and number of diarrhea cases

District	Hospital bed availability ratio per population	Number of diarrhea cases
Tasikmalaya	1:5.997	51.490
Garut	1:2.425	72.459
Cianjur	1:2.824	69.090

Spatial reach analysis using service area analysis generated a map of hospital accessibility based on travel time by four-wheeled vehicles, categorized into two intervals: ≤30 minutes (accessible) and 31–60 minutes (moderately accessible). This mapping reveals a critical spatial dimension in evaluating environmental disparities in healthcare service provision.

Figure 4 shows that most areas in the southern, eastern, and southwestern parts of Tasikmalaya Regency fall outside the optimal hospital service coverage. Subdistricts such as Culamega, Cipatujah, Cikalong, Pancatengah, and Cikatomas require more than 60 minutes to reach the nearest hospital, either SMC Hospital or Singaparna Medika Citrautama

Hospital. With the region's predominantly hilly topography and limited road infrastructure, these areas are at high risk of delays in emergency medical response, particularly for infectious diseases like diarrhea, which are highly time-sensitive.

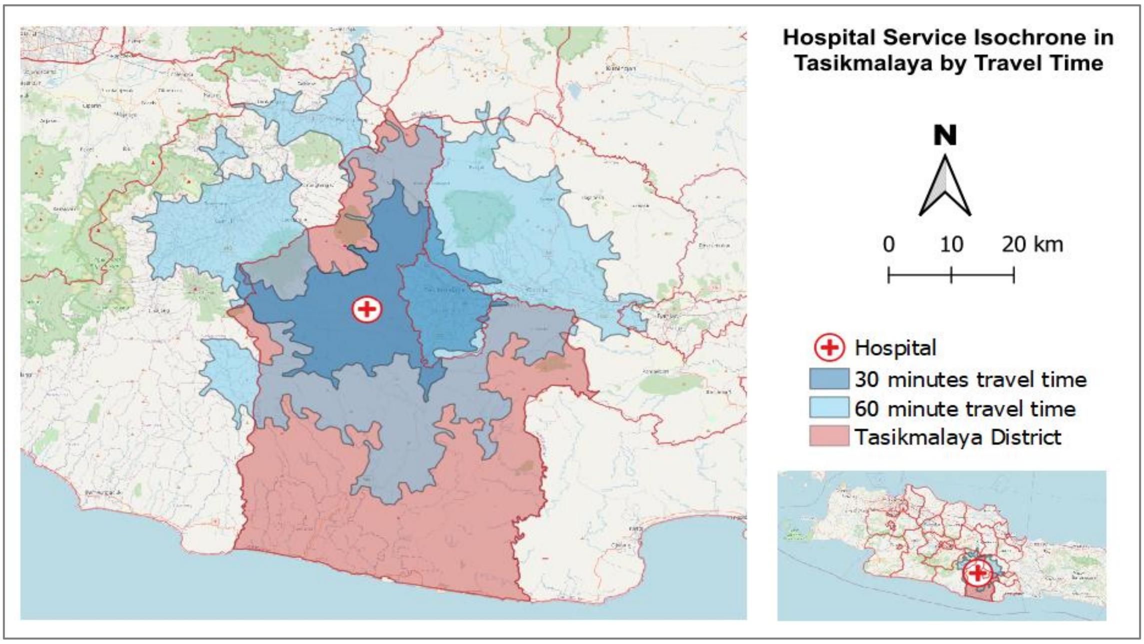

Fig. 4. Isochrone map of hospital accessibility in Tasikmalaya Regency by travel time using four-wheeled vehicles

In addition, central parts of Tasikmalaya Regency - including Bojonggambir, Bantarkalong, Karangnunggal, Cibalong, Parungponten, Jatiwaras, Taraju, Sodonghilir, and Cigalontang - are also categorized as moderately accessible, with travel times ranging from 31 to 60 minutes to reach the hospital. The high service load on the sole public hospital in the area further indicates the potential for overcapacity, especially during seasons marked by spikes in environmentally-related disease cases. Therefore, government intervention as outlined in Natsir (2025) is urgently needed to address these accessibility gaps.

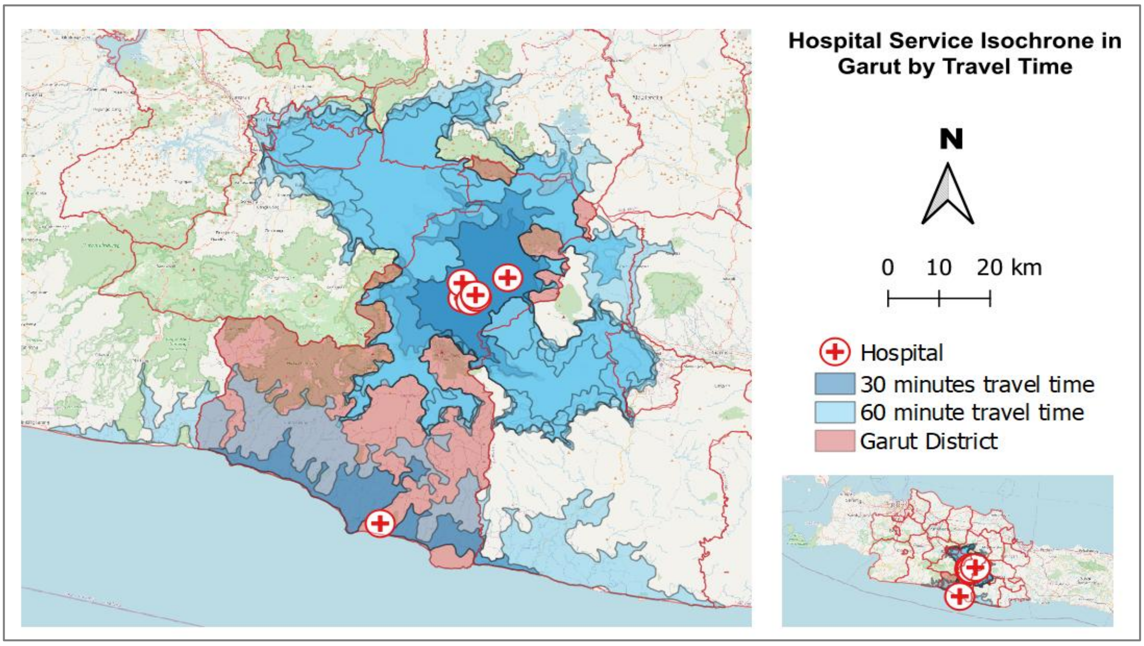

Fig. 5. Isochrone map of hospital accessibility in Garut Regency by travel time using four-wheeled vehicles

The hospital service coverage map in Garut Regency (Figure 5) reveals significant spatial disparities in healthcare accessibility across the region. The central areas- including the subdistricts of Cibiuk, Cibatu, Leuwigoong, Banyuresmi, Tarogong Kaler, Wanaraja, Tarogong Kidul, Garut Kota, Bayongbong, and Cilawu - have relatively short travel times to hospitals (<30 minutes), due to a high concentration of healthcare facilities in the regency's administrative center. Adequate access is also observed in parts of the southern region served by RSUD Pameungpeuk, such as Mekarmukti, Cikelet, and Cibalong subdistricts.

However, access disparities are highly pronounced in the southern and southwestern parts of Garut, especially in subdistricts such as Talegong, Cisewu, Bungbulang, Pamulihan, Pakenjeng, Cisompet, Peundeuy, Cihurip, and Singajaya, where most areas lie outside the 60-minute travel time coverage to the nearest hospital. Harsh terrain and the lack of transportation infrastructure exacerbate spatial isolation in these regions, which are generally composed of hilly landscapes and steep coastal zones. This phenomenon reflects broader environmental inequalities in access to basic infrastructure, particularly healthcare services, which may increase the risk of morbidity and mortality among vulnerable populations such as children under five and the elderly, especially during outbreaks of waterborne diseases like diarrhea.

The concentration of hospitals in the administrative center also suggests potential overcapacity at RSUD Dr. Slamet and RS Intan Husada, particularly during seasonal case surges. Only one hospital is located in the southern part of the regency, despite the wide geographic coverage and low accessibility of the surrounding areas. This issue has attracted media attention, with reports stating that residents in remote southern Garut must travel up to six hours to access basic healthcare services (Susanti, 2025). This situation underscores the urgent need for environmentally responsive and spatially just healthcare infrastructure development to ensure public health system resilience, particularly in the face of climate change and rising infectious disease burdens.

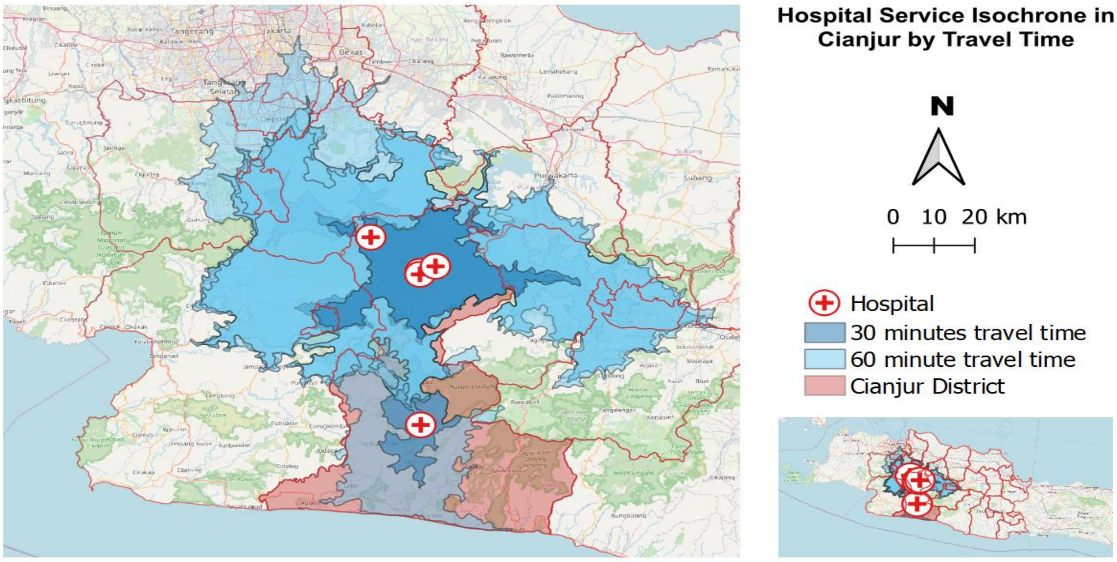

Fig. 6. Isochrone map of hospital accessibility in Cianjur Regency by travel time using four-wheeled vehicles

The hospital service coverage map in Cianjur Regency (Figure 6) highlights a clear spatial disparity between the northern and southeastern regions. The northern areas, including the subdistricts of Cipanas, Sukaresmi, Cikalong Kulon, Cugenang, Karang Tengah, Mande, Ciranjang, Haurwangi, Cilaku, Cibeber, and Gekbrong, exhibit optimal accessibility, with travel times to hospitals of less than 30 minutes. This is supported by a higher concentration of healthcare facilities in the region, including RSUD Sayang, RSUD Cimacan, and several private hospitals in the Cipanas area.

Conversely, the central to southern parts of Cianjur Regency face significant limitations in healthcare access. With only one regional hospital in this area (RSUD Pagelaran), most subdistricts - such as Agrabinta, Cidaun, Naringgul, Campakamulya, Cikadu, Pasirkuda, and Caringin - fall outside the ideal travel time coverage zone. Many of these areas require more than 60 minutes to reach the nearest hospital. The topography, dominated by hilly terrain and steep coastal zones, along with limited transportation infrastructure, further exacerbates interregional accessibility gaps.

This spatial inequality directly impacts the effectiveness of treatment for infectious diseases such as diarrhea, which require prompt medical response. Delayed referrals from areas with low access can increase the risk of complications and mortality, particularly among vulnerable groups such as children and the elderly. In the context of an equitable and resilient healthcare system, these conditions underscore the need to strengthen health service infrastructure in remote regions. Local government authorities have acknowledged this issue, as noted by the Regent of Cianjur, who emphasized the need to build at least three additional hospitals to support population growth and ensure equitable access to basic healthcare services (Selamet, 2024). Accordingly, the use of spatial data-driven analysis such as this is essential to support inclusive and sustainable healthcare infrastructure planning.

3.3 Environmental risk clustering of diarrhea incidence in West Java: PCA-based spatial typology

This subsection aims to identify the spatial typology of districts and cities in West Java Province based on a combination of environmental and socioeconomic risk factors influencing the incidence of diarrhea. A Principal Component Analysis (PCA) approach was applied to reduce multicollinearity among variables, followed by clustering methods to map areas based on the similarity of risk profiles. This strategy aligns with the principles of environmental epidemiology, which emphasize identifying spatial vulnerabilities to support region-based interventions.

Data from five environmental indicators—including access to improved sanitation, access to clean water, and the types of toilet facilities (private, shared, and communal or no toilet), as well as a poverty indicator were analyzed across 27 districts/cities. Preliminary normality and correlation tests revealed high multicollinearity among certain variables, particularly between private and shared toilet facilities. To address this without eliminating any variables, PCA was conducted, preceded by the identification and removal of three extreme outliers. This process resulted in 24 administrative units serving as the basis for further analysis.

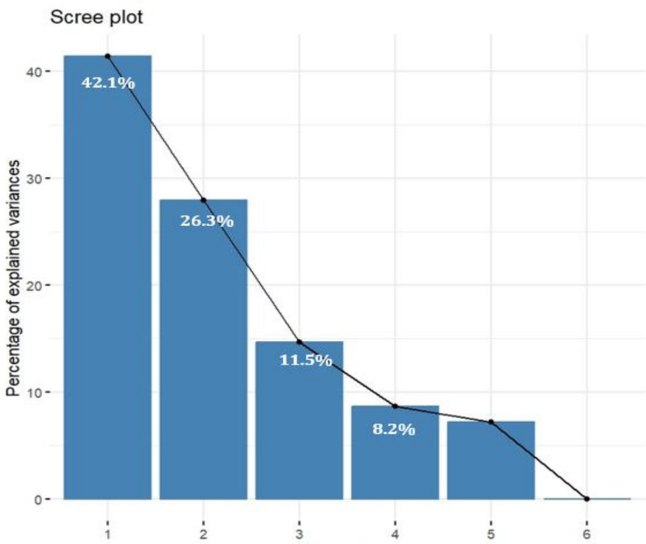

Fig. 7. *Scree plot* PCA

The Scree Plot result (Figure 7) shows that four principal components (PC1–PC4) explain more than 80% of the total variance and were subsequently used to construct a composite risk index. This composite risk index in each principal component is derived from a weighted combination of six indicators. These weights, referred to as eigenvalues, were used to calculate new indicator values for the 24 districts/cities included in the analysis. A Pearson correlation test confirmed that the four newly generated indicators are uncorrelated, thus enabling spatial clustering based on the PCA output.

The Elbow Method was applied to determine the optimal number of clusters, which resulted in three main clusters. Meanwhile, three districts/cities previously identified as extreme outliers were grouped into a separate fourth cluster. Therefore, the total number of diarrhea risk clusters amounted to four clusters. Table 3 presents the classification of districts and cities in West Java Province based on dominant diarrhea risk factors. Clusters 1 to 3 were formed through PCA-based clustering, while Cluster 4 comprises the extreme outlier units. The separation of this fourth cluster follows the spatial epidemiological principle of isolating high-risk outlier areas that deviate significantly from mainstream patterns. This approach is consistent with established practices in spatial risk classification for environmental diseases, which recommend treating extreme areas as distinct units of analysis and intervention (Sunaryo, 2015).

Districts/cities highlighted in bold in Table 3 represent the three areas with the highest number of diarrhea cases in West Java Province in 2023, namely: Bogor Regency (151,930 cases, Cluster 3), Bandung Regency (100,470 cases, Cluster 2), and Bekasi Regency (87,410 cases, Cluster 3). The results indicate that high-case areas are distributed across multiple clusters. This suggests that, based on 2023 data, no single cluster was dominant in determining diarrhea incidence. Rather, all risk factors appear to be interrelated and contribute collectively to the total number of cases.

Table 3. Clustering of districts/cities in West Java Province based on diarrhea risk factors, 2023. Districts/cities in bold indicate the area with the highest number of diarrhea cases within each cluster.

Cluster	Regency/City	Dominant diarrhea risk factors
1	Subang Regency, Bekasi Regency, Bogor City, Bekasi City, Depok City, Banjar City	Private toilet facilities (positive), Proportion of population in poverty (negative)
2	Bandung Regency, Indramayu Regency, Bandung City, Cirebon City, Cimahi City	Shared toilet facilities (positive), Access to improved drinking water (positive), Communal/no toilet facilities (negative)
3	Bogor Regency, Sukabumi Regency, Garut Regency, Ciamis Regency, Kuningan Regency, Majalengka Regency, Sumedang Regency, Purwakarta Regency, Karawang Regency, West Bandung Regency, Pangandaran Regency, Sukabumi City, Tasikmalaya City	Access to improved drinking water (positive), Access to improved sanitation (negative), Proportion of population in poverty (positive)
4 (extrem outlier)	Cianjur Regency, Tasikmalaya Regency, Cirebon Regency	Private toilet facilities (moderate–low), Communal/no toilet facilities (high–very high), Proportion of population in poverty (high)

In addition, the positive and negative signs of the eigenvalues within each cluster further support the interpretation of this study's findings. In Cluster 1, the risk factor *proportion of population in poverty* shows a negative influence (-0.6270), indicating an inverse relationship with the number of diarrhea cases. This may be attributed to the fact that Cluster 1 is predominantly composed of large urban areas in West Java, where the population tends to enjoy relatively better socioeconomic conditions. In contrast, in Cluster 3, the same poverty indicator shows a positive influence (0.6294), suggesting a direct relationship with diarrhea incidence, consistent with the composition of Cluster 3, which includes many rural regencies in West Java.

However, each cluster includes at least one region with the highest number of diarrhea cases in the province. This reinforces the notion that risk factors are interrelated in contributing to diarrhea incidence, no single risk factor operates in isolation. The PCA-based clustering results in this study indicate that spatial variation in environmental risk does not always exhibit a linear relationship with diarrhea case numbers. These findings align with the study by Sadiq et al. (2023), which demonstrated that economic variables such as household wealth significantly contribute to reducing diarrhea risk, yet their effects can be moderated by other variables such as population density and nutritional status. In the context of West Java, urban areas with lower poverty levels tend to have stronger mitigation capacity, although they may still experience a high disease burden. This highlights the importance of an integrative approach in interpreting environmental epidemiological data, one that goes beyond the prevalence of a single risk factor.

Moreover, the PCA-based spatial clustering approach enables a more holistic risk mapping, in line with the principles of spatial epidemiology, which emphasize the importance of recognizing the geographical distribution of disease to support more targeted interventions (Elliott & Wartenberg, 2004). This approach allows the identification of spatial vulnerability zones based on combinations of environmental and socioeconomic factors, which often remain undetected in single-variable analyses. Thus, the findings of this study not only reflect spatial vulnerability but also provide evidence-based input for regional and risk-based healthcare infrastructure planning.

This research also reinforces the urgency of utilizing spatial analysis in the study of environmentally-related diseases in Indonesia. Spatial analysis using GIS not only aids in visualizing case data but also supports decision-making in disease control through the identification of high-risk areas, case clustering, and assessment of healthcare service accessibility (Sunaryo, 2015). The PCA clustering results in this study demonstrate that the availability of sanitation and clean water facilities does not always directly correlate with lower case numbers, unless accompanied by adequate infrastructure quality and environmental health education. This aligns with the findings of Nugroho et al. (2023) in their spatial analysis of leptospirosis, which showed that disease incidence is not limited to densely populated areas but also occurs in rural regions with limited sanitation access, highlighting the importance of a spatial approach that comprehensively considers environmental context.

From a sustainability and long-term risk management perspective, PCA-based spatial analysis is also relevant within the framework of integrated environmental management. As explained by Fatkhullah et al.(2022) in their study on reducing community vulnerability, spatially-based health risk mitigation must involve systematic and cross-sectoral environmental data management. The availability of high-quality environmental data, coupled with appropriate statistical methodologies such as PCA, can generate a more realistic and scientifically accountable risk landscape. This approach opens opportunities for strengthening risk zone-based intervention strategies and supports integrating environmental, spatial, and public health issues into a sustainable and multidisciplinary solution framework.

3.4 Integration of accessibility and environmental risk: synthesis of findings and policy implications

Previous spatial analyses revealed disparities in both healthcare service capacity and environmental risk distribution related to diarrhea. When the overlay of the hospital accessibility index and the PCA-based risk cluster map is compared (Figure 8), it becomes evident that most areas with low accessibility levels (travel time >30 minutes) tend to fall within high-risk clusters (Clusters 3 and 4). For instance, Tasikmalaya and Garut Regencies not only demonstrate limited spatial hospital coverage but are also categorized within clusters characterized by dominant risk factors such as poor sanitation access and high poverty rates. This reinforces the link between limited healthcare access and environmental exposure to diarrhea risk, as shown in Fariza et al. (2021), which highlights how spatial inequality worsens disease burden, especially in infrastructure-stressed areas.

These findings align with the spatial epidemiology framework articulated by Elliott & Wartenberg (2004), which posits that geographic variation in disease incidence cannot be fully understood without considering the spatial dimension of healthcare accessibility as a driver of structural vulnerability. The study underscores the importance of geographical correlation approaches to identify regions with limited access to medical facilities and high environmental exposure. The overlay approach combining accessibility index and environmental risk clusters enriches the analysis and supports area-based intervention planning.

Furthermore, this study supports the principles of disaster risk management focused on spatially driven prevention, as discussed by Del Pinto et al. (2024) and Sunaryo (2015). They emphasize that overlay-based vulnerability mapping—between access capacity and environmental exposure - is a crucial step in designing adaptive intervention systems, especially in regions with complex geographic and socioeconomic challenges. By identifying areas under dual pressure - low access to medical services and high environmental risk—this research advocates for strengthening public health resilience strategies that are responsive to geographic contexts. This is also in line with recommendations by Sadiq et al. (2023), which emphasize the importance of understanding spatial relationships to target interventions toward the most vulnerable populations.

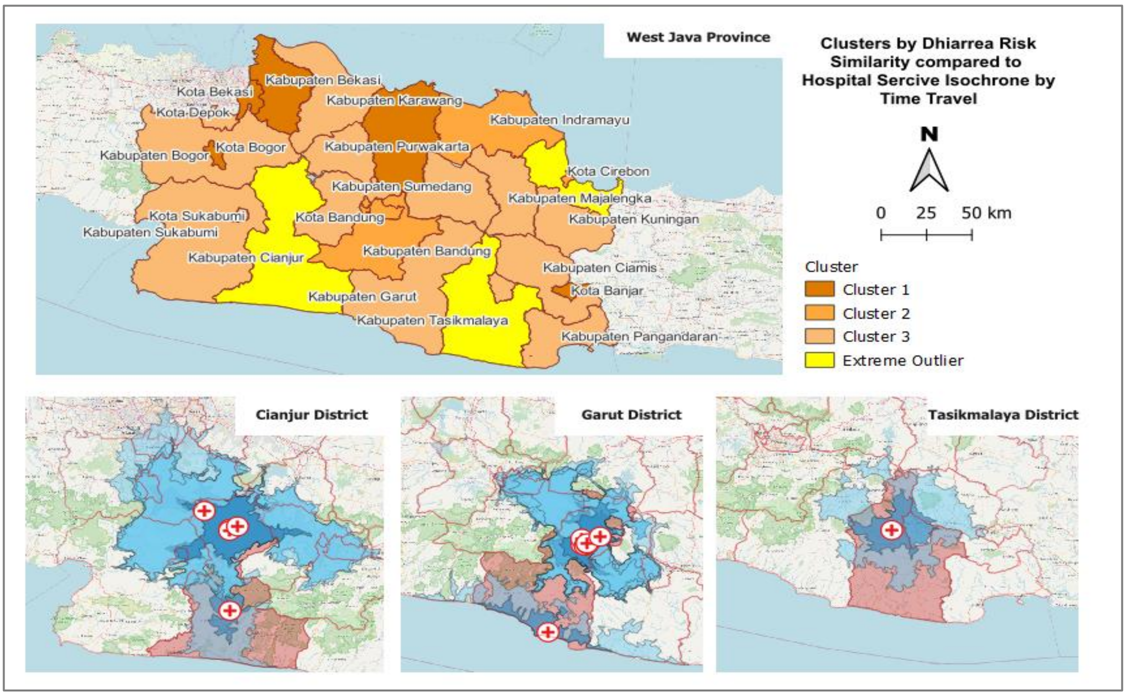

Fig. 8. Cluster map of districts/cities based on diarrhea risk factors (2023) and hospital accessibility map (travel time) in Tasikmalaya, Garut, and Cianjur Regencies

The policy implications of these findings underscore the importance of adopting adaptive spatial governance strategies grounded in environmental risk. This is particularly relevant for regions bearing a dual burden of low accessibility and high vulnerability to environmental diseases such as diarrhea. This approach aligns with the Health Infrastructure Climate Risk Assessment Framework (HICRAF) by Puntub et al. (2024), which emphasizes the need for systematic risk mapping, the use of composite socio-environmental indicators, and iterative scenario-based planning. In the context of West Java Province, the implementation of spatial vulnerability-based policy can be realized through the development of cross-sectoral intervention roadmaps to improve health infrastructure in red zones—areas falling under high-risk clusters and with low service accessibility.

Additionally, inclusive and technology-driven adaptive strategies should be prioritized to bridge spatial-structural gaps in healthcare services. The study by Effendi et al. (2024) shows that effective two-way communication in telemedicine significantly improves patient health outcomes. Therefore, health policies must promote digital health literacy within communities and provide clinical communication training for medical personnel, especially in remote, outermost, and disadvantaged areas (3T regions). These findings are consistent with the open innovation approach proposed by Futri & Naruetharadhol (2025) which advocates for multi-stakeholder collaboration in the development of digital health services. This requires strengthening the digital ecosystem through telemedicine regulation, ICT upgrades, and data protection.

Moreover, lessons from developing countries such as India in system-based emergency disease management, examined by Chandrashekhar et al. (2020) demonstrate that success in acute cardiac referral systems in constrained settings has been achieved through low-cost technologies like mHealth and multi-sectoral partnerships. This approach is highly relevant to Indonesia in managing environmentally related diseases such as diarrhea. Thus, the health system must go beyond infrastructure, focusing on referral innovation, incentives for remote health workers, and emergency transport networks. This strategy will help build a more resilient, spatially adaptive, and inclusive health system for vulnerable populations.

Under the framework of the National Medium-Term Development Plan (RPJMN) 2025–2029 which explicitly includes digital health transformation as a national priority, the opportunity to build an open innovation ecosystem becomes increasingly tangible, structured, and target-oriented. The operational directives laid out in Presidential Regulation No. 28/2024 further strengthen this framework by comprehensively regulating healthcare service provision, information systems, health technologies, financing, community participation, and cross-sectoral oversight. Annexes I–IV in RPJMN support regional adaptation, while PP No. 28/2024 mandates system integration and data interoperability. With this regulatory synergy, health digitalization is no longer a sectoral initiative but becomes a mainstream component of national development, collaborative, data-driven, and open to innovation at all levels of government.

This study has several limitations that should be acknowledged. First, the spatial and non-spatial data are limited to the district/city level, which restricts the ability to capture intra-regional variations in risk and accessibility at the village or community level. Second, the quality and completeness of data on sanitation, toilet facilities, and water sources, especially from secondary sources, may affect the accuracy of the clustering results. Third, the travel-time-based spatial analysis relied on estimated average vehicle speeds and did not account for real-time road conditions. Future research should apply multi-scale methods with high-resolution data, field surveys, and machine learning to improve intervention targeting.

4. Conclusions

This study reveals the existence of spatial disparities between healthcare service capacity, spatial accessibility to hospitals, and environmental risk associated with diarrhea incidence in West Java Province. The overlay of the healthcare accessibility index and environmental risk clusters shows that areas with low access tend to also have high-risk profiles, particularly in Tasikmalaya, Garut, and Cianjur Regencies. The integration of spatial analysis with Principal Component Analysis (PCA) and regional clustering enables the identification of vulnerable zones in a more objective and data-driven manner. This supports an evidence-based approach to planning healthcare infrastructure development, especially in regions with geographic constraints and high socioeconomic pressures. The findings indicate that intervention strategies must be directed toward areas facing dual burdens, not only through the construction of physical health facilities but also by leveraging technology, telemedicine, and strengthening cross-sectoral collaboration. The

National Medium-Term Development Plan (RPJMN) 2025–2029 and Presidential Regulation No. 28/2024 have established a regulatory framework that promotes adaptive and risk-based digital health transformation. As such, this study not only provides a comprehensive mapping of spatial vulnerabilities but also offers policy recommendations that are more responsive to geographic contexts and local social dynamics.

Acknowledgement
The authors would like to thank the Dean and the teaching staff of the Faculty of Mathematics and Natural Sciences, Universitas Indonesia, for their guidance, academic support, and the valuable opportunity to carry out this research within the academic environment of the faculty.

Author Contribution
Conceptualization, G.M.L., A.O., and D.H.; Methodology, G.M.L. and A.O.; Software, G.M.L.; Validation, A.O. and D.H.; Formal Analysis, G.M.L. and A.O.; Investigation, A.O. and D.H.; Resources, A.O. and D.H.; Data Curation, A.O. and D.H.; Writing – Original Draft Preparation, G.M.L., A.O., and D.H.; Writing – Review & Editing, G.M.L.; Visualization, G.M.L.; Supervision, D.H.; Project Administration, G.M.L. and D.H.

Funding
This research received no external funding.

Ethical Review Board Statement
Not available.

Informed Consent Statement
Not available.

Data Availability Statement
All data used in this study were obtained from publicly available secondary sources, including the West Java Provincial Health Profile 2023, West Java in Figures 2024, the Indonesian Geospatial Information Agency (BIG), OpenStreetMap, and Google Earth Pro. These datasets are cited accordingly in the manuscript. No new primary data were generated by the authors.

Conflicts of Interest
The authors declare no conflict of interest.

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