Civil Engineering and Architecture 14(3): 1805-1818, 2026 http://www.hrpub.org
DOI: 10.13189/cea.2026.140328

Rural Drinking-Water Service Continuity under Flood and Landslide Hazards: A GIS Analysis of PAMSIMAS Pipeline Networks

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Received December 5, 2025; Revised March 19, 2026; Accepted April 15, 2026

Cite This Paper in the Following Citation Styles

(a): *[1] Petrizal, Nurhasan Syah, Heldi, Eri Barlian, Indang Dewata, Early Septiningsih, Azhari Syarief, Aprizon Putra , "Rural Drinking-Water Service Continuity under Flood and Landslide Hazards: A GIS Analysis of PAMSIMAS Pipeline Networks," Civil Engineering and Architecture, Vol. 14, No. 3, pp. 1805 - 1818, 2026. DOI: 10.13189/cea.2026.140328.*

(b): *Petrizal, Nurhasan Syah, Heldi, Eri Barlian, Indang Dewata, Early Septiningsih, Azhari Syarief, Aprizon Putra (2026). Rural Drinking-Water Service Continuity under Flood and Landslide Hazards: A GIS Analysis of PAMSIMAS Pipeline Networks. Civil Engineering and Architecture, 14(3), 1805 - 1818. DOI: 10.13189/cea.2026.140328.*

Abstract This study aims to assess changes in improved drinking-water access before and after the March 2024 floods and landslides, and map the exposure of Rural Drinking-Water Supply Systems (RDWSS) infrastructure, such as intakes, reservoirs, pipelines, and service connections, to flood and landslide hazards, within the governance context of the Community-Based Drinking Water and Sanitation Programme (PAMSIMAS) and Resilient Village Program (DESTANA)-type disaster preparedness in rural disaster-prone settings. Quantitative descriptive and spatial-analytical methods were applied, using administrative records from the Public Works and Spatial Planning Office (PUTR) of Pesisir Selatan Regency, systematic field observations, verification of service connections, and Global Positioning System (GPS)-based mapping of intakes, reservoirs, and pipelines. These data were combined with flood and landslide-hazard maps in a Geographic Information System (GIS) to identify infrastructure segments and service areas most exposed to disruption. Before the disaster, improved drinking-water coverage exceeded 94.96% across the three analysed villages, largely due to PAMSIMAS and the Regional Drinking Water Company (RDWC) expansion. After the disaster, coverage fell to 32.30% in Duku and 20.45% in Duku Utara, while Barung-Barung Belantai Tengah retained 76.35%. GIS overlays show that approximately 31.6 km of pipelines lie in landslide-prone zones and about 19.9 km in flood-prone areas, with the most severe failures where intakes and transmission lines cross unstable slopes or river corridors (e.g., Pasar Minggu, Kampung Tanjung, Ranah Talawi, Duku Benteng). These results demonstrate that pipeline-dependent systems are highly vulnerable when alignments, crossings, and intake locations are not planned and protected using hazard information.

Keywords Rural Drinking-Water Supply, Floods and Landslides, Service Continuity, Spatial Analysis, Resilience

1. Introduction

Access to safe drinking water is a fundamental human right and a critical determinant of public health, social stability, and sustainable development [1–3]. However, in recent decades, global drivers such as climate change, population growth, environmental degradation, and natural disasters have increasingly undermined its availability and reliability [4]. These pressures reduce both the quality and quantity of freshwater sources while heightening the vulnerability of water-supply infrastructure, particularly in hazard-prone regions [5]. Ensuring safe drinking water is therefore not only an urgent humanitarian need but also a long-term development challenge.

Disasters have repeatedly demonstrated their capacity to disrupt drinking water-supply systems. In Europe, the 2021 floods in Germany and Belgium destroyed pipelines and reservoirs, leaving hundreds of thousands without access to safe water [6,7]. In Africa, prolonged droughts in Somalia, Sudan, and Kenya forced communities to depend on unsafe water sources, exacerbating public-health crises [8]. In Asia, floods have frequently collapsed distribution systems, as seen during Typhoon Haiyan in the Philippines (2013), which left millions without clean water [9,10]. These experiences highlight that water-supply systems lacking resilience cannot ensure service continuity under intensifying climate-induced hazards.

Indonesia, one of the world's most disaster-prone countries, is highly exposed to earthquakes, tsunamis, floods, volcanic eruptions, and landslides [11–14]. Such hazards frequently damage rural water facilities, from raw-water intakes to transmission and distribution networks. The 2018 Lombok and Palu earthquakes, for instance, destroyed numerous community systems and left residents reliant on unsafe alternatives [15]. In West Sumatra, steep slopes, fragile soils, and heavy rainfall contribute to recurrent floods and landslides [16–18]. A recent example occurred in March 2024, when flash floods and landslides in Pesisir Selatan Regency devastated intakes, pipelines, and reservoirs in Koto XI Tarusan Sub-district [19]. Affected communities faced immediate shortages of safe water, underscoring the need for resilient Rural Drinking-Water Supply Systems (RDWSS) that integrate technical improvements, disaster mitigation, adaptive planning, and community-based management, supported by hazard-exposure spatial analysis using Geographic Information Systems (GIS).

Over the past two decades, Indonesia has introduced major programmes to expand rural water access. The Community-Based Drinking Water and Sanitation Programme (PAMSIMAS) has significantly increased coverage through participatory management [20,21]. However, programme planning and performance metrics have tended to emphasise service expansion and functionality. At the same time, disaster risk reduction and hazard-informed asset protection are often treated as add-ons rather than design requirements [22]. The Disaster-Resilient Village Programme (DESTANA), initiated by Indonesia's National Agency for Disaster Management (BNPB), aims to strengthen community preparedness, early warning, and local response capacity [23–25]. Yet, DESTANA mechanisms are rarely operationalised around critical lifeline services such as rural drinking-water systems, and they are not systematically embedded in PAMSIMAS routines such as network siting, maintenance scheduling, tariff setting, and post-disaster rapid assessment. This fragmentation means that while PAMSIMAS delivers infrastructure and community management, the resilience of these systems remains weak when disasters strike. Without synergy, water facilities remain vulnerable during floods and landslides, and communities lack coordinated mechanisms to maintain service continuity after disasters.

Conceptually, RDWSS resilience requires alignment between programme governance and engineering decisions. Governance arrangements influence where networks are extended, how critical assets are safeguarded, how disruptions are reported, and how repairs are financed. In this study, spatial hazard asset overlays are treated as a decision-support layer that can inform governance actions, for example, helping PAMSIMAS implementers and local government to prioritise protection/relocation of exposed components, adjust maintenance schedules, and pre-position response resources, while enabling DESTANA-type preparedness to operationalise early-warning and contingency plans into location-specific measures at the most exposed intakes, river crossings, and service areas.

To address these gaps, this study adopted quantitative descriptive and spatial-analytical methods to examine how floods and landslides affect RDWSS in Koto XI Tarusan Sub-district, Pesisir Selatan Regency, West Sumatra Province, Indonesia. This study aims to assess changes in improved drinking-water access before and after the March 2024 floods and landslides, and map the exposure of RDWSS infrastructure, such as intakes, reservoirs, pipelines, and service connections, to flood and landslide hazards, within the governance context of PAMSIMAS and DESTANA-type disaster preparedness in rural disaster-prone settings. The novelty of the study lies in combining quantitative descriptive analysis with GIS-based mapping of RDWSS assets and service-connection exposure, and explicitly linking these spatial patterns to rural water-supply and disaster-resilience programmes.

2. Methods

This study employed a quantitative descriptive and spatial-analytical design to assess drinking water-supply systems resilience and community preparedness [26–28]. Data were obtained through field observations, verification of service connections, Global Positioning System (GPS)-based mapping of intakes, reservoirs, and pipelines, and direct measurements of key assets. These data were analyzed descriptively to characterize pre- and post-disaster conditions. Additionally, spatial analysis using GIS was employed to map hazard exposure, infrastructure distribution, and service coverage at the village level. By overlaying landslide and flood risk maps with the locations of springs, reservoirs, pipelines, and household connections, GIS produced spatially explicit insights into vulnerabilities. This spatial evidence provided locational accuracy and visual clarity, directly linking asset exposure to observed service disruptions and supporting the development of targeted strategies for RDWSS.

2.1. Population and Samples

The study area covers four disaster-prone villages in Koto XI Tarusan Sub-district, Pesisir Selatan Regency, with a combined population of 10,783 people, namely Duku (4,770), Duku Utara (2,547), Barung-Barung Belantai Tengah (1,556), and Barung-Barung Belantai Selatan (1,910). Population figures were verified against BPS village profiles and the Public Works and Spatial Planning Office (PUTR) of Pesisir Selatan Regency (2023) administrative registers. The earlier preliminary total (8,783) excluded Barung-Barung Belantai Selatan. These villages were purposely selected because they are directly exposed to floods and landslides and are key areas for drinking water supply systems. From a spatial-analytical perspective, the population distribution and settlement pattern in these villages can be mapped and analysed against hazard exposure and infrastructure conditions [29,30]. For the quantitative and spatial components, the primary unit of analysis was the RDWSS infrastructure rather than individual households. All identified intakes, reservoirs, transmission and distribution pipelines, and registered service connections in the four villages were inventoried using field-based observations, GPS surveys, and administrative records from the PUTR (2023), the Regional Drinking Water Company (RDWC), and PAMSIMAS operators.

To support interpretation of these data, purposive consultations were held following Makwana et al. [31] with community members and local stakeholders, including household users, PAMSIMAS and DESTANA committees, village officials, and technical agencies such as RDWC and the Regional Disaster Management Agency (BPBD). To minimise ambiguity between demographic population figures and the study's analytical units, population totals were used only to describe the study context, while service-coverage and disruption estimates were derived from the verified RDWSS service-connection registers and field verification. Improved-access results are therefore reported only for villages with complete pre- and post-disaster coverage records (Duku, Duku Utara, and Barung-Barung Belantai Tengah), whereas Barung-Barung Belantai Selatan is included only in the infrastructure exposure inventory and hazard-overlay analysis because its pipeline segments and hazard corridors are connected to the same RDWSS network environment.

Potential biases in field data collection were addressed through a simple quality-assurance protocol, namely 1) a standardised observation checklist and repeated site visits for critical assets (intakes, river crossings, and major breaks); 2) GPS point/track logging with accuracy screening and photo-documentation for each mapped asset; 3) triangulation of RDWC/PAMSIMAS registers with on-site confirmation of service-connection functionality; and 4) reconciliation meetings with village operators to resolve discrepancies (e.g., inactive connections, relocated households, or segments not safely accessible during post-disaster conditions). Residual bias may remain where access was constrained by slope instability or safety considerations. However, such segments were flagged during inventorying and treated conservatively in the interpretation.

2.2. Data Analysis

Quantitative data on population, service coverage, and the condition of RDWSS before and after the March 2024 events were compiled in spreadsheets and analysed descriptively to characterise changes in improved drinking-water access and system performance at the village level. Spatial analysis was applied to map disaster exposure and the vulnerability of rural water-supply infrastructure. The geographic coordinates of facilities such as intakes, transmission pipelines, reservoirs, and distribution networks were collected through GPS surveys and subsequently processed using ArcGIS software. An overlay was performed between landslide- and flood-hazard maps and the spatial distribution of water infrastructure to identify zones most at risk of disruption. The vulnerability assessment was quantified using an exposure-based index derived from the GIS overlays.

Data validation was conducted before analysis to strengthen the reliability of descriptive statistics and GIS-derived exposure measures, such as 1) administrative coverage figures and service-connection lists were cleaned through range checks, duplicate removal, and reconciliation against village-level registers. A subset of connections was then field-verified to confirm operational status after the disaster; 2) GPS-based asset locations and pipeline tracks were screened for positional accuracy and checked for topology errors (gaps/overlaps) and coordinate consistency before overlay, and pipeline lengths were cross-checked between GIS outputs and field notes for major trunk segments; and 3) Hazard layers were harmonised to consistent classes and coordinate reference systems before intersection. A simple sensitivity check was applied to the composite VI by comparing equal-weight results with alternative weighting scenarios (e.g., higher weight on landslide exposure in steep terrain) to confirm that village rankings were robust to reasonable weighting changes. Such segments were flagged during inventorying and interpreted conservatively. For each village or scheme j, a composite Vulnerability Index (VI_j) was calculated as the mean of the relative landslide-exposed and flood-exposed pipeline shares (equal weights):

$$VI\_j = 0.5 \times (L\_ls,j / \Sigma L\_ls) + 0.5 \times (L\_fl,j / \Sigma L\_fl)$$

Where VI_j is the composite vulnerability index for unit j; L_ls,j is the length of pipelines intersecting landslide-prone zones in unit j; L_fl,j is the length intersecting flood-prone zones in unit j; and Σ denotes the corresponding totals across the study area. The index is dimensionless and ranges from 0 to 1, enabling relative comparison across villages/schemes.

Qualitative information from purposive consultations and operator debriefings was recorded as field notes and synthesised using simple thematic coding (e.g., disruption pathways, coping behaviours, repair constraints, and institutional coordination). These qualitative themes were then used to interpret the quantitative coverage changes, to explain why specific hotspots failed, and to frame programme-relevant recommendations alongside the GIS results. This approach was used to systematically link hazard intensity with the spatial distribution of infrastructure based on four assembled GIS layers. First, flood- and landslide-hazard maps from the provincial BPBD were processed through overlay and reclassification to produce consistent intensity classes for analysis. Second, the RDWSS, including transmission and distribution mains, was compiled from RDWC and PAMSIMAS records, then digitised and verified with targeted GPS surveys. Third, intake and reservoir locations were collected via GPS and georeferenced to the project coordinate system. Fourth, administrative boundaries from the Statistics Bureau (BPS) were harmonised through spatial joins and minor topology edits to align with the network geometry. The resulting overlay of hazard classes and infrastructure layers revealed pipeline segments and nodes most exposed to disruption and provided a basis for identifying priority areas for reinforcement, maintenance scheduling, and contingency planning. The composite index was used to rank villages by relative vulnerability and to contextualise patterns of severe service disruption following the March 2024 events.

3. Results

The study was conducted in four villages located in Koto XI Tarusan Sub-district, Pesisir Selatan Regency, West Sumatra Province. Geographically, the study area lies between 100°28′–100°34′ East Longitude and 1°00′–1°02′ South Latitude. These villages represent diverse geographical settings, ranging from hilly uplands and lowland plains to coastal areas. Such diversity makes the region highly vulnerable to hydro-meteorological hazards, particularly floods and landslides. With hilly terrain and pockets of lowland plains, it is highly susceptible to landslides on steep slopes, posing risks to water infrastructure.

The RDWSS in Koto XI Tarusan Sub-district relies on springs, reservoirs, and PAMSIMAS networks. However, disaster events often disrupt supply due to infrastructural damage, contamination, and limited storage. Reliance on small-scale systems provides essential access but leaves communities vulnerable, while inadequate maintenance remains a barrier to sustainable service delivery. More details can be seen on the map in Fig. 1.

3.1. Changes in Improved Drinking-Water Access before and after the Disaster

According to the World Health Organization (WHO) [32], safe drinking water must comply with physical, chemical, and microbiological quality standards to ensure that consumption does not pose short- or long-term health risks. Administrative data from the PUTR (2023) show that, before the March 2024 disaster, coverage of improved drinking-water access in the three analysed villages, namely Duku, Duku Utara, and Barung-Barung Belantai Tengah, was relatively high. Most households had access to piped or non-piped protected facilities, although a small proportion remained unserved.

Before the floods and landslides, improved drinking-water access ranged between 94.96% and 97.36%. In this study, "improved drinking-water access" follows the PUTR (2023) service-coverage classification, where improved access includes piped services and protected non-piped sources (e.g., protected wells/springs). Duku recorded the highest improved-access coverage (97.36%), with piped services accounting for 87.34% of households. Specifically, in Duku, improved access (97.36%) consists of 87.34% piped services and 10.02% protected non-piped sources, while 2.64% remains unserved/unimproved (PUTR administrative register, 2023). Therefore, the piped-service percentage is reported as a component (subset) of the overall improved-access indicator, rather than a separate or contradictory measure. By contrast, Barung-Barung Belantai Tengah still relied heavily on non-piped sources such as protected wells and springs. These figures reflect the positive impact of national programmes such as PAMSIMAS and the RDWC, which have significantly expanded rural water-service coverage. Table 1 summarises the pre-disaster coverage and service-type composition used to generate Fig. 2. More details can be seen in Table 1 and Fig. 2.

However, the March 2024 floods and landslides caused severe disruption to RDWSS. Damage to intake structures, transmission pipelines, and reservoirs led to a sharp decline in service coverage, particularly in villages that depended heavily on gravity-fed piped networks. More details can be seen in Table 2.

Validation of post-disaster coverage values was cross-checked against RDWC/PAMSIMAS service-connection registers and spot-verified during field visits. Following the disaster, improved drinking-water access dropped drastically in Duku (32.30%) and Duku Utara (20.45%). In contrast, Barung-Barung Belantai Tengah maintained 76.35% coverage, as a larger share of its distribution network lay outside the most severely

Figure 3. Map of landslide risk and RDWSS pipeline distribution

Although Fig. 3 clarifies that landslide exposure is a dominant driver of disruption, particularly where steep alignments, unstable slopes, and vulnerable intake approaches coincide with main transmission corridors, the overlay also suggests that landslide risk alone does not fully describe RDWSS vulnerability. Several critical trunk segments and settlement-serving branches descend from upland terrain into valley bottoms, where the network repeatedly interacts with river corridors through crossings, parallel reaches, and low-lying distribution zones. In these settings, flood processes introduce distinct failure pathways that can compound the effects of slope instability. Whereas landslides typically generate abrupt breaks, burial, and access failures on steep slopes, floods tend to disrupt service through channel migration, scour around buried pipelines, debris impact on exposed joints and crossing structures, and prolonged operational shutdowns when turbidity and contamination risks rise at intakes. Importantly, these flood-related mechanisms can extend service interruption even when the damaged pipe length appears limited, because affected assets often function as bottlenecks for multiple downstream users.

From an analytical standpoint, separating landslide and flood exposure helps avoid attributing all service losses to slope failure when some interruptions may be driven by river-corridor dynamics, especially in villages connected to lowland floodplains. The spatial contrasts among neighbouring systems in Table 3, where some schemes recovered rapidly while others experienced prolonged collapse, also indicate that vulnerability depends not only on hazard intensity but on how alignments, crossings, and key nodes are situated across hazard environments. Therefore, to complete the hazard profile and interpret recovery constraints, the analysis next examines flood exposure using the same GIS-based overlay approach. Fig. 4 overlays flood risk with RDWSS intake points, reservoirs, and transmission pipelines, enabling identification of segments exposed to inundation and river processes as well as segments subject to dual hazards (landslides and floods). This combined perspective strengthens the case for hazard-informed planning, including reinforcement of crossings, protection of intake approaches, and strategic rerouting of exposed corridors. More details can be seen on the map in Fig. 4 below.

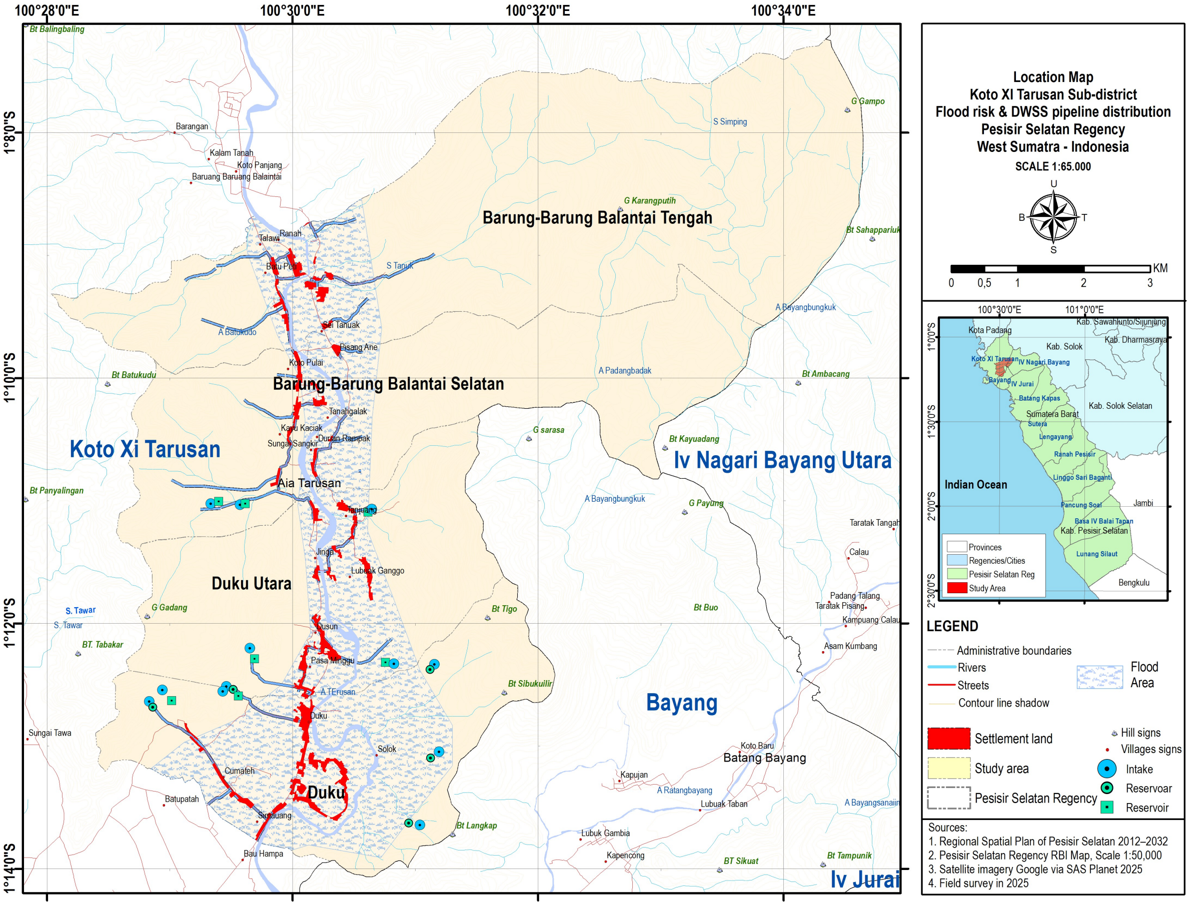

Figure 4. Map of flood risk and RDWSS pipeline distribution

To strengthen the quantitative use of the vulnerability formulation, scheme-level exposure was synthesised into a composite VI based on the relative share of pipeline length intersecting landslide- and flood-prone zones. This index summarises exposure patterns into a comparable 0–1 scale across villages.

Across the four schemes, VI ranged from 0.185 to 0.303, with Barung-Barung Belantai Tengah and Duku Utara showing the highest relative exposure. These rankings provide a transparent, quantitative basis for prioritising reinforcement and preparedness actions across schemes. More details can be seen in Table 4.

3.3. Post-Disaster Condition of RDWSS Service Connections

To assess the direct impacts on households, verification of RDWSS Service Connections (SC) was carried out across disaster-affected hamlets. The assessment recorded the status of metered and non-metered connections and whether they remained functional or were disrupted. More details can be seen in Table 5.

Household consultations corroborated these patterns, where users in fully disrupted villages/hamlets reported switching to rainwater harvesting and temporary delivery, while households in partially functional villages/hamlets prioritised protected wells/springs as short-term buffers until piped service stabilised. The findings in Table 5 indicate that, under disaster conditions, a large number of service connections became non-functional. Pasar Minggu experienced a complete service collapse, with all households classified as non-SC (disrupted) following intake and pipeline damage. Duku Benteng, despite having the highest number of metered connections, also experienced system failure due to intake destruction and loss of transmission capacity. In contrast, hamlets such as Koto Pulai and Air Sonsang demonstrated higher levels of resilience, with a greater proportion of SC remaining functional, although temporary service interruptions still occurred during peak hazard conditions. These patterns are consistent with the GIS overlay results, which showed that hamlets and schemes with pipelines located in high-hazard zones were the most affected by service disruptions.

Table 4. Composite vulnerability index (VI) derived from hazard–pipeline intersections

Village/Scheme	Pipelines in landslide zones (m)	Pipelines in flood zones (m)	Landslide share (%)	Flood share (%)	Composite VI (0–1)
Duku	5,265.51	4,064.51	16.66	20.35	0.185
Duku Utara	7,502.96	6,452.13	23.74	32.30	0.280
Barung-Barung Belantai Tengah	9,374.93	6,191.13	29.66	30.99	0.303
Barung-Barung Belantai Selatan	9,464.38	3,267.75	29.94	16.36	0.232

Source: Survey results and GIS overlay calculations, 2025.

Table 5. Post-disaster condition of RDWSS Service Connections (SC)

Villages/Hamlet	Households	SC Total	Non SC	Metered SC	SC (Disrupted)	SC (Non-disrupted)
Ranah Talawi	177	99	17	-	49	50
Koto Pulai	108	108	0	-	93	15
Air Sonsang	54	54	28	-	42	12
Sungai Sangkir	80	66	14	-	62	4
Tanah Galak	49	47	2	0	7	40
Kampung Tanjung	160	121	39	-	71	50
Pasar Minggu	164	164	0	-	0	164
Duku Benteng	258	213	45	213	213	0
Kampung Jongah	–	–	–	–	–	
Benteng	362	345	17	-	195	150

Source: Survey results and data analysis, 2025.

3.4. Linking Spatial Exposure to Programme Actions (PAMSIMAS–DESTANA)

This study's GIS outputs (hazard-asset intersection maps and segment-level exposure counts) are not only technical diagnostics. They can also be used as decision-support inputs to help align routine rural water management under PAMSIMAS with community disaster preparedness under DESTANA. Howard et al. [26] argue that resilience in Water, Sanitation, and Hygiene (WASH) systems becomes actionable when risk information is linked to routine management decisions and investment prioritisation. This perspective is also supported by earlier work linking WASH investment decisions with disaster risk reduction [33]. This framing is consistent with the multi-actor WASH hazard-resilience strategies described by Johannessen et al. [34]. To make this alignment operational, the GIS results can be applied in three practical ways, namely 1) The identified hotspot segments (e.g., river crossings and unstable slopes where failures cluster) can be translated into a prioritised asset register for PAMSIMAS operators and local government, supporting Operations and Maintenance (O&M) scheduling, targeted protection works, and transparent budgeting for risk-proofing; 2) The same hotspots can be integrated into DESTANA contingency planning by linking early-warning triggers to specific intakes and crossings, and by pre-assigning response protocols (e.g., temporary chlorination, tanker distribution, alternative sources, and rapid damage assessment) to the most exposed service areas; and 3) By tracking pre- and post-disaster service-connection functionality alongside spatial exposure, local institutions can monitor not only physical damage but also service-continuity outcomes. This interpretation is consistent with evidence on service continuity and institutional determinants reported by DuChanois et al. [35], as well as the social and organisational factors highlighted by Krishnan [27]; Machado et al. [36]. Overall, these steps support coordinated actions between PAMSIMAS and DESTANA to protect critical RDWSS assets and maintain service continuity.

Disruption pathways (as experienced by users and operators). Field consultations consistently described three recurring service-failure pathways, namely 1) intake inaccessibility and damage after slope failures; 2) river-crossing instability leading to pipe breaks and prolonged repair windows; and 3) precautionary shutdowns during extreme turbidity and contamination risk, even where visible structural damage was limited. These narratives align with the mapped hotspot segments and support interpreting exposure not only as a structural risk but also as an operational risk. Coping strategies and short-term buffering. Households reported switching to rainwater harvesting, protected wells/springs, and ad-hoc distribution during outages. Importantly, villages with a larger protected non-piped share before the disaster (Table

1) described these sources as practical buffers, whereas villages dominated by piped conveyance reported fewer immediate substitutes and a higher reliance on emergency delivery.

Recovery constraints and logistics. Operators emphasised that repair duration depended heavily on road access, labour availability, and the availability of spare parts for crossings and intake approaches. Where access roads and steep alignments failed, repairs were delayed, even when the damaged segment was short, reinforcing why service losses did not scale linearly with pipeline length alone.

Governance and coordination signals. Village and programme stakeholders noted that routine asset registers and maintenance planning prioritised expansion and functionality checks. At the same time, hazard information was not consistently embedded in siting decisions, crossing protection works, or financing arrangements. These qualitative observations motivate the governance-oriented recommendations, particularly the integration of GIS hazard overlays into PAMSIMAS asset registers and DESTANA contingency plans.

4. Discussion

Baseline service composition helps explain why post-disaster service losses were highly uneven across villages. As shown in Table 2, pre-disaster improved access exceeded 94.96% in all villages, but the share delivered through piped networks differed markedly (Duku 87.34% piped; Duku Utara 79.59%; Barung-Barung Belantai Tengah 57.18%), implying different levels of dependence on long transmission alignments and river crossings. This dependence is consistent with the sharp drops after the March 2024 floods and landslides, where Duku and Duku Utara experienced the steepest declines, while Barung-Barung Belantai Tengah retained higher coverage.

These patterns indicate that expansion-led gains under PAMSIMAS and RDWC can mask structural fragilities when hazard information is not embedded in intake siting, crossing design, redundancy, and maintenance financing. Interpreting pre-disaster coverage together with exposure hotspots, therefore, shifts the discussion from "how much coverage exists" to "how that coverage is delivered and how quickly it can fail under hazard forcing". Eum et al. [37] show that river crossings can concentrate hydraulic stress through local scour, debris impact, and bed-material mobilisation during peak flows, which makes crossing segments structurally sensitive even when adjacent reaches remain intact. This is consistent with the clustered disruptions observed at crossing-like segments and near intake approaches in the mapped exposure hotspots. Arrighi et al. [38] found that flood impacts on water distribution systems often extend beyond the inundated footprint because functional dependencies propagate pressure loss and service interruption across connected areas, so disruption severity can depend on network configuration rather than exposed length alone. Rasekh and Brumbelow [39] noted that pressure deficits and hydraulic transients can also increase vulnerability to contamination events and customer-level service interruption, which helps explain why some schemes experienced widespread disruption even when exposure was spatially concentrated. LeChevallier et al. [40] showed that transient low or negative pressure can create intrusion pathways at leaks and fittings, which reinforces the need to interpret flood exposure as both a structural and a water-quality risk for RDWSS.

DuChanois et al. [35] emphasize that service continuity is shaped by more than pipe condition, including operational capacity and recovery logistics, so a purely hazard-intersection metric should be interpreted as a screening indicator rather than a probabilistic damage model. In this paper, the composite vulnerability index operationalises exposure by normalising intersecting pipeline lengths by village totals and then synthesising landslide and flood exposure into a comparable 0 to 1 score across schemes, which addresses the reviewer's concern that a simple expression is mathematically trivial when it is not linked to a measurable index. Chaudhuri and Choudhury [41]; Zheng et al. [42] explain that buried pipes on unstable slopes can fail through ground displacement, loss of embedment, bending, tensile stress, and joint separation, which provides a mechanism-based explanation for why failures clustered at steep terrain segments identified in the landslide overlays. According to Krishnan [27]; Machado et al. [36], social and organisational factors can strongly influence post-disaster repair time and recovery outcomes, which explains why disruption severity does not always scale linearly with exposure length.

Rickert et al. [43] emphasize that climate-resilient water safety planning requires hazard information to be embedded into routine monitoring, operational controls, and emergency response, which supports interpreting the mapped hotspots as priorities for both preventive maintenance and preparedness actions. Kumpel and Nelson [44] reported that intermittency and low-pressure conditions are widely associated with higher contamination risk and service instability, which is relevant where flood-driven pressure disruptions and rapid repairs can increase water-quality vulnerability. Machado et al. [36] found that the performance of community-managed drinking-water systems is closely tied to management practices, financial governance, and institutional support, which aligns with the need to integrate exposure results into budgeting, maintenance planning, and coordination arrangements. Mahmoud et al. [45] showed that intrusion risks increase under low operating pressure and transient events, which strengthens the interpretation that flood exposure should be analysed in terms of both physical damage pathways and contamination pathways.

5. Conclusions

Beyond quantifying exposure, the GIS outputs provide a governance-ready evidence base to align PAMSIMAS asset management with DESTANA preparedness so that protection works, routine maintenance, and rapid post-disaster recovery can be prioritised in the most hazard-exposed segments and service areas. This study shows that the March 2024 floods and landslides severely disrupted access to safe drinking water in Koto XI Tarusan Sub-district. Before the disaster, improved drinking-water coverage (piped services plus protected non-piped sources, PUTR 2023) exceeded 94.96% across the three analysed villages, largely due to the expansion of PAMSIMAS-supported rural water-supply systems and RDWC services. After the disaster, however, coverage fell sharply to 32.30% in Duku and 20.45% in Duku Utara, while Barung-Barung Belantai Tengah retained 76.35% coverage. These changes highlight the vulnerability of pipeline-dependent systems to extreme events, especially where networks traverse unstable slopes and floodplains. GIS-based spatial analysis confirms that the steepest service losses occurred where RDWSS assets intersected high-hazard zones. Approximately 31.6 km of pipelines were found in landslide-prone areas and about 19.9 km in flood-prone areas, exposing nearly all villages to elevated risks of infrastructure damage. Field verification further documented the collapse of systems such as Pasar Minggu, Kampung Tanjung, Ranah Talawi, and Duku Benteng, contrasted with faster recovery in schemes where intakes and network segments were less exposed to hazard hotspots. The service-connection assessment shows that large numbers of SCs became non-functional in highly exposed hamlets, while locations such as Koto Pulai and Air Sonsang demonstrated relatively higher resilience, albeit with temporary interruptions. Overall, the findings demonstrate that RDWSS are highly vulnerable when pipeline alignments, river crossings, and intake locations are not planned and protected using hazard information. Strengthening resilience, therefore, requires an integrated, hazard-informed governance and engineering approach. Key priorities include 1) re-routing, elevating, or armouring pipelines at river crossings and unstable slopes, and protecting or relocating intakes away from scour and debris paths while adding redundancy through looped networks, emergency bypasses, and protected storage; 2) embedding GIS-based hazard overlays into RDWSS asset planning and maintenance, and linking asset registries with routine GPS audits and early-warning thresholds; 3) tightening institutional coordination by coupling community-based PAMSIMAS operations with DESTANA-type preparedness, including clear roles for emergency chlorination, tanker or rainwater contingencies, and rapid damage assessment; and 4) establishing financial safeguards, such as contingency funds, adaptive tariffs for risk-proofing, and transparent asset-management routines. Implemented together, these measures can help sustain service continuity, reduce the depth and duration of outages, and build long-term resilience of RDWSS in disaster-prone settings. Qualitative consultation themes reinforced these priorities by highlighting that recovery speed was constrained by access logistics, spare-part availability, and routine governance practices that did not systematically incorporate hazard information into siting, protection works, and financing. These insights underscore that resilience is simultaneously a technical and institutional challenge.

Acknowledgements

The authors would like to express their sincere gratitude to the Government of Pesisir Selatan Regency for providing support and facilitation during the fieldwork activities. Special thanks are extended to the RDWC of Pesisir Selatan Regency for their valuable data, technical assistance, and insights into the condition of rural water supply systems. Their contributions were instrumental in the successful completion of this study.

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