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Assessing wastewater treatment performance in small island contexts: a multi-aspect evaluation of Tidung Besar Island, Indonesia

Penilaian kinerja pengolahan limbah cair di konteks pulau kecil: evaluasi multi-aspek Pulau Tidung Besar, Indonesia

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Abstrak.
Pulau-pulau kecil menghadapi tantangan keberlanjutan yang unik dalam pengelolaan air limbah domestik akibat keterbatasan sumber daya, ruang, dan tingginya kerentanan ekologi, di sisi lain penilaian komprehensif multi-dimensi masih jarang dilakukan. Studi ini mengatasi kesenjangan tersebut melalui penilaian multi-aspek sistem pengelolaan air limbah domestik di Pulau Tidung Besar, Indonesia, dengan mengintegrasikan aspek teknis, kelembagaan, lingkungan, dan sosial di pulau kecil yang padat penduduk dan berbasis pariwisata tersebut. Pendekatan eksploratif-deskriptif diterapkan dengan mengombinasikan teknik observasi, wawancara *stakeholder*, kuesioner, dan analisis data sekunder selama periode Maret 2024 hingga Agustus 2025. Data dianalisis menggunakan metode triangulasi, statistik deskriptif, dan sintesis kualitatif. Studi ini mengungkap paradoks kritis bahwa meskipun terdapat penerimaan masyarakat yang kuat dan infrastruktur yang mapan berupa empat instalasi pengolahan air limbah yang melayani 831 sambungan rumah, sistem masih menghadapi tantangan lingkungan yang serius. Konsentrasi amonia dan *total coliform* masing-masing mencapai 163 dan 137 kali lipat dari baku mutu yang diprasyaratkan. Tantangan teknis meliputi kelebihan kapasitas di zona padat, kerusakan peralatan, dan cakupan layanan yang belum menyeluruh, serta pemantauan yang masih lemah. Secara sosial, rendahnya pemahaman masyarakat tentang pengelolaan air limbah domestik kontras dengan tingkat kepuasan yang tinggi. Temuan ini menegaskan bahwa penerimaan masyarakat saja tidak cukup dan diperlukan solusi terintegrasi lintas dimensi.

Kata kunci: pulau kecil, limbah domestik, kinerja pengolahan, kapasitas kelembagaan, penilaian multi-aspek

Abstract.
Small islands face unique sustainability challenges in domestic wastewater management (DWM) due to limited resources, confined space, and high ecological vulnerability, yet comprehensive multi-dimensional assessments remain scarce. This study addresses this gap through a multi-aspect assessment of the DWM system on Tidung Besar Island, Indonesia, integrating technical, institutional, environmental, and social dimensions in a densely populated tourism-based small island. An exploratory-descriptive approach was employed, combining field observations, stakeholder interviews, questionnaires, and secondary data analysis from March 2024 to August 2025. Data were analyzed through triangulation methods, descriptive statistics, and qualitative synthesis. The study reveals a critical paradox that despite strong community acceptance and established infrastructure comprising four wastewater treatment plants serving 831 house connections, the system faces severe environmental challenge. Ammonia and total coliform exceed quality standards by up to 163 and 137 times. Technical challenges include overcapacity in high-demand zones, equipment failures, and incomplete service coverage, while institutional monitoring remains weak. Socially, most residents lack wastewater knowledge yet report high satisfaction based on visible improvements. This reveals that community acceptance alone cannot serve as a reliable indicator of system success. The study also demonstrates that small island wastewater management requires integrated solutions addressing interconnected challenge across all dimensions simultaneously.

Keywords: small island, domestic wastewater, treatment performance, institutional capacity, multi-aspect assessment

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1. INTRODUCTION

Small Island Developing States (SIDS) and small island communities face critical sustainability challenges stemming from their unique geographic, economic, and demographic characteristics. Indonesia, as the world's largest archipelagic nation with over 17,000 islands (Geospatial Information Agency 2024; Indonesian Central Statistics Agency 2024), exemplifies these challenges particularly in islands with high population density and tourism-dependent economies. According to Law Number 27 of 2007, small islands in Indonesia are defined as islands with an area of less than 2,000 km^2 along with their entire ecosystem (President of Republic of Indonesia 2007). While these islands possess high coastal and marine biodiversity (Kurniawan *et al.* 2016) and unique ecological value, they are simultaneously constrained by limited resources, geographic isolation, and heightened vulnerability to both natural disasters and anthropogenic pressures (Nunn and Kumar 2018; Thomas *et al.* 2020).

Among these challenges, domestic wastewater management (DWM) emerges as a critical yet inadequately addressed issue in small island contexts. Domestic wastewater is a primary contributor to aquatic pollution (Widyarani *et al.* 2022), and inadequate management systems on small island can severely affect marine ecosystem health (Wear and Thurber 2015; Prost-Boucle *et al.* 2023; Maliga *et al.* 2025). The urgency is amplified in islands with dense residential populations and intensive tourism activities, where seasonal wastewater strains existing infrastructure (Rodríguez-Alcántara *et al.* 2024). Despite this recognized importance, research on wastewater management in small island settings remains scarce, with most studies focusing on solid waste management (Willmott and Graci 2016) or water resource sustainability (Crisman and Winters 2023; Mycoo and Roopnarine 2024).

Tidung Besar Island, located in the Seribu Islands Administrative Regency of DKI Jakarta Province, Indonesia, represents a critical case study for small island DWM. With a total area of 50.13 ha (Fauzanabri *et al.* 2021), the island is characterized by relatively high residential density and intensive tourism activities. The population has increased from 4,587 in 2015 to 5,978 in 2025 (Hayati *et al.* 2020; Jakarta Provincial Population and Civil Registration Agency 2025; Tidung Island Village Administration 2025), representing a 30.32% growth over ten years and is the most populous island in Seribu Islands.

Beyond its residential function, Tidung Besar Island serves as a major tourist destination, attracting 65,258 visitors in 2024 (Seribu Islands Kominfotik Sub-Agency 2025), making it the second-largest tourist destination in Seribu Islands. Ecologically, the island possesses valuable coastal and marine resources, including mangroves, seagrass beds, and coral reefs that support diverse marine life (Hayati *et al.* 2020). This combination of population growth, tourism intensity, and ecological sensitivity creates a complex management scenario where inadequate wastewater treatment threatens both marine ecosystem integrity and the tourism-dependent economy.

Despite the establishment of DWM infrastructure on Tidung Besar Island in recent years, infrastructure presence alone does not guarantee sustainability or effectiveness. Existing research on wastewater treatment sustainability emphasizes the necessity of multi-dimensional assessment frameworks encompassing technical, environmental, social, and institutional dimensions (Muga and Mihelcic 2008; Kalbar *et al.* 2012; Molinos-Senante *et al.* 2014; Omran *et al.* 2021; Rahimzade *et al.* 2025). However, previous studies have largely emphasized technical assessments and energy efficiency (Liu *et al.* 2013; Garfí *et al.* 2017; Onyeka Eleweuwa *et al.* 2025), and indicator-based evaluations (Muga and Mihelcic 2008; Kalbar *et al.* 2012; Molinos-Senante *et al.* 2014; Omran *et al.* 2021; Rahimzade *et al.* 2025), which fail to capture the integrated complexity of wastewater systems.

More critically, while sustainability assessment frameworks have been widely developed, their application to small island contexts remains minimal. Recent small island research has increasingly emphasized developing island nations (Robinson and Gilfillan 2017; Poinen and Bokhoree 2022; Crisman and Winters 2023), whereas studies specifically addressing Indonesian small islands remain limited. This leaves a significant knowledge gap regarding how DWM systems perform within Indonesia's island-specific constraints of confined space, limited financial and technical resources, and dependence on external supplies (Prost-Boucle *et al.* 2023; SMILO 2023).

This study aims to assess the performance of the domestic wastewater management system on Tidung Besar Island by integrating technical, institutional, environmental and social dimensions into a comprehensive multi-aspect framework. The novelty lies in examining the interconnections between these dimensions, revealing how infrastructure adequacy, institutional capacity, environmental compliance, and community acceptance compound to affect overall system performance within a densely populated Indonesian small island context where such research remains scarce.

Methodologically, the study employs a rigorous multi-reference quality standard approach, evaluating effluent quality against domestic wastewater standards, seawater quality for maritime tourism, and marine biota protection criteria. Thus, addressing the institutional disconnect where operational management typically references only domestic wastewater standards while ecological reality necessitates comprehensive seawater quality protection. The findings are intended to serve as foundational knowledge for enhancing domestic wastewater management on Tidung Besar Island and to provide transferable lessons for other small islands globally facing similar sustainability challenges.

2. METHODOLOGY

2.1. Research time and location

This research is a case study conducted on domestic wastewater management (DWM) in Tidung Besar Island, which is located to the north of Java Island or Jakarta Capital City of Indonesia, specifically within the Seribu Islands area. The research focuses on Tidung Besar Island among many small islands in the Seribu Islands, as it is considered to have adequate conditions for this study, namely the largest population, intensive tourism activity, and a large number and capacity of DWM infrastructure. This study adopts an exploratory-descriptive approach, well-suited for investigating and characterizing domestic wastewater management (DWM) in small island contexts, where prior research remains scarce (Creswell 2014). This aligns with previous research (Al-Khatib *et al.* 2010) employing similar methods in assessing municipal solid waste management systems.

2.2. Research method

The primary data were collected through field observations and social surveys. The observations examined the DWM infrastructure (wastewater treatment plant/WWTP, pipe network, and supporting facilities), wastewater sources (residential, lodging or homestay, public facilities, and government offices), and the island's environmental conditions. Semi-structured interview by applying in-depth interview techniques (DiCicco-Bloom and Crabtree 2006; Ahlin 2019; Ruslin *et al.* 2022) were conducted with key respondents, consisting of WWTP managers and local community leaders. Questionnaires were administered to all respondents, including both key and general respondents (residents), to assess perceptions of DWM on Tidung Besar Island and to identify attitudes, knowledge gaps, and behavioural intentions (Wilson 2014; Brace 2018). Respondents included 6 WWTP managers from the Seribu Islands Water Resources Sub-Agency, 5 local community leaders (up to the village level), and 45 residents representing various types of wastewater sources. They were selected through purposive sampling based on the study objectives and stakeholder relevance. This approach ensured that information on DWM was obtained from multiple perspectives, providing a balanced and comprehensive representation of all stakeholder views. To facilitate the presentation of results, each respondent group was coded as [A] for WWTP managers, [B] for local community leaders, and [C] for residents.

The secondary data used is WWTP internal documents, such as managerial information, technical information, and monitoring report. Other than that, literature review also applied for supporting the study including scientific articles journals, theses, government or local databases/documents, government regulation, etc.

The various process of data collection and sources of data is intended as a method triangulation and data source triangulation to examine the accuracy of information and obtain reliable information, as described by Rahardjo (Rahardjo 2010). Additionally, inter-researcher triangulation involving multiple enumerators was also conducted under shared guidelines ensured consistent, objective-aligned results and enriched the data with findings closer to the truth (Rahardjo 2010). This set of triangulation approaches was applied to validate findings before proceeding with the data analysis.

After data validated, the data were processed through the following steps, including data reduction, display data, data presentation, and continue to conclusion drawing and verification (Bungin 2003). During the data display and presentation stages, data analysis was conducted using approaches tailored to the type of data. Qualitative analysis was applied to non-numerical data, producing narrative descriptions, illustrative photographs, and explanatory diagrams. In contrast, quantitative analysis was performed on numerical data using descriptive statistical methods, including frequencies, percentages, comparisons, and ratios. The data were processed and visualized using Microsoft Excel and the results presented in the form of charts, graphs, and matrices or tables. Integrating qualitative and quantitative analyses provided a comprehensive understanding of domestic wastewater management (DWM), encompassing technical, institutional, environmental, and social aspects, particularly regarding system performance and stakeholder perspectives. The entire methodological framework, covering data collection and analysis from March 2024 to August 2025, is summarized in the research flow diagram in **Figure 1**.

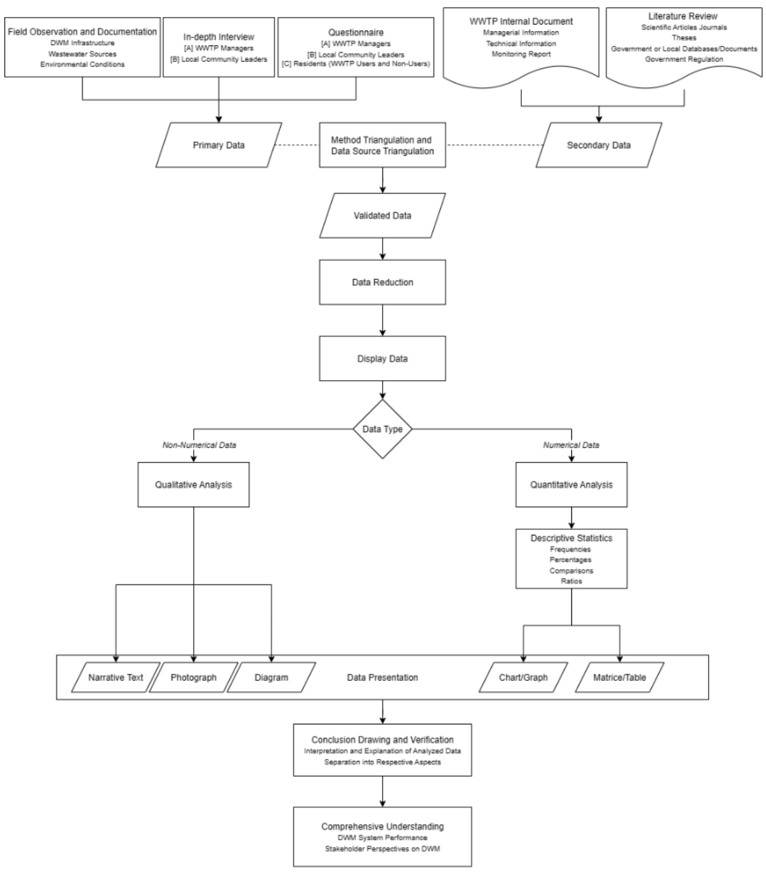


Figure 1. Research flow diagram.

3. RESULT AND DISCUSSION

3.1. Result

3.1.1. Technical and institutional aspect

Currently, Tidung Besar Islands already have the infrastructure of DWM with the existence of 4 domestic WWTPs (east, north, west, and south zones) (**Figure 2**). WWTP east and north zones were built by the Water Resources Agency of DKI Jakarta Province in 2016, followed by the west and south zones in the following year. The technical basis for the construction of these WWTPs refers to Regulation of the Minister of Public Works and Public Housing No. 4 of 2017 concerning the Implementation of Domestic Wastewater Management Systems (Minister of Public Works and Public Housing 2017).

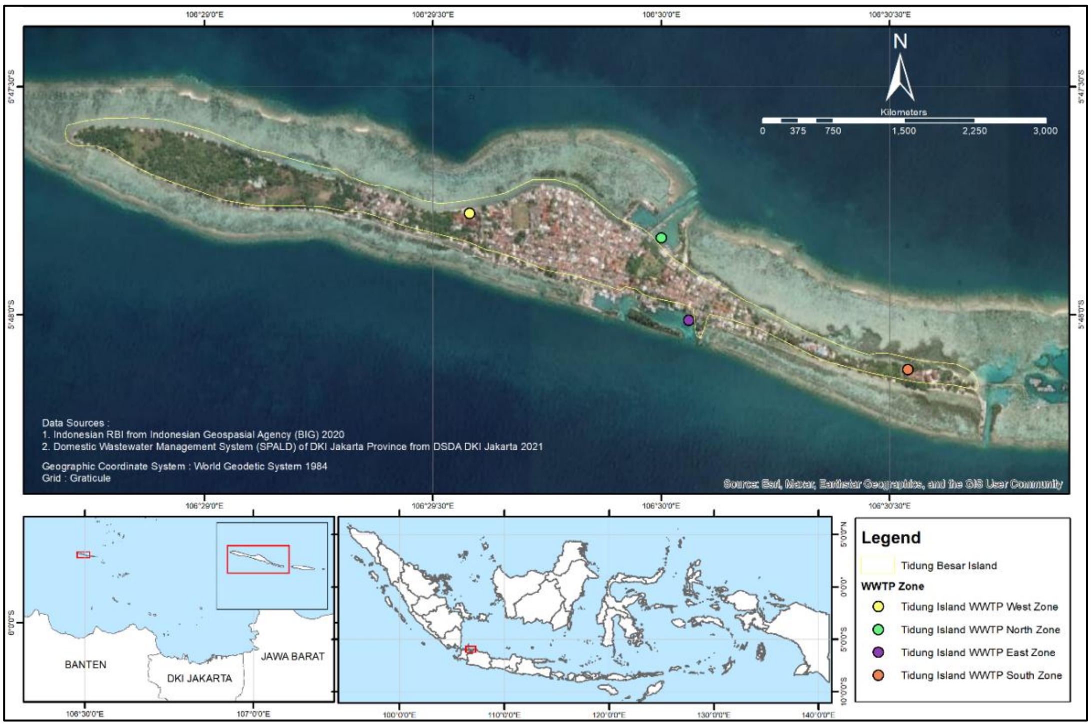


Figure 2. Distribution of WWTP facilities in Tidung Besar Island, Seribu Islands, Jakarta, Indonesia (Source: Water Resources Agency of DKI Jakarta Province (2024))

The DWM system on Tidung Besar Island operates as a communal WWTP with an extensive piping network that connects to various buildings and activities, including residential areas or houses, lodgings/homestays, public facilities (school, mosque, sports hall, park, health center, dock, etc.), and government offices (**Figure 3**). Each building is equipped with a control tank ("*bak kontrol*"/BK) to accommodate grey water and black water.

The domestic wastewater from each BK is subsequently conveyed through a series of manholes, which serve as primary conduits for channelling the flow toward the WWTP. Assisted by a lift pump, the wastewater is transferred to the WWTP, where it initially accumulates in the sump pit before entering the subsequent anaerobic-aerobic treatment processes. This integrated treatment configuration ensures gradual and stable pollutant removal, resulting in improved effluent quality (Kassab *et al.* 2010; Englande *et al.* 2015).

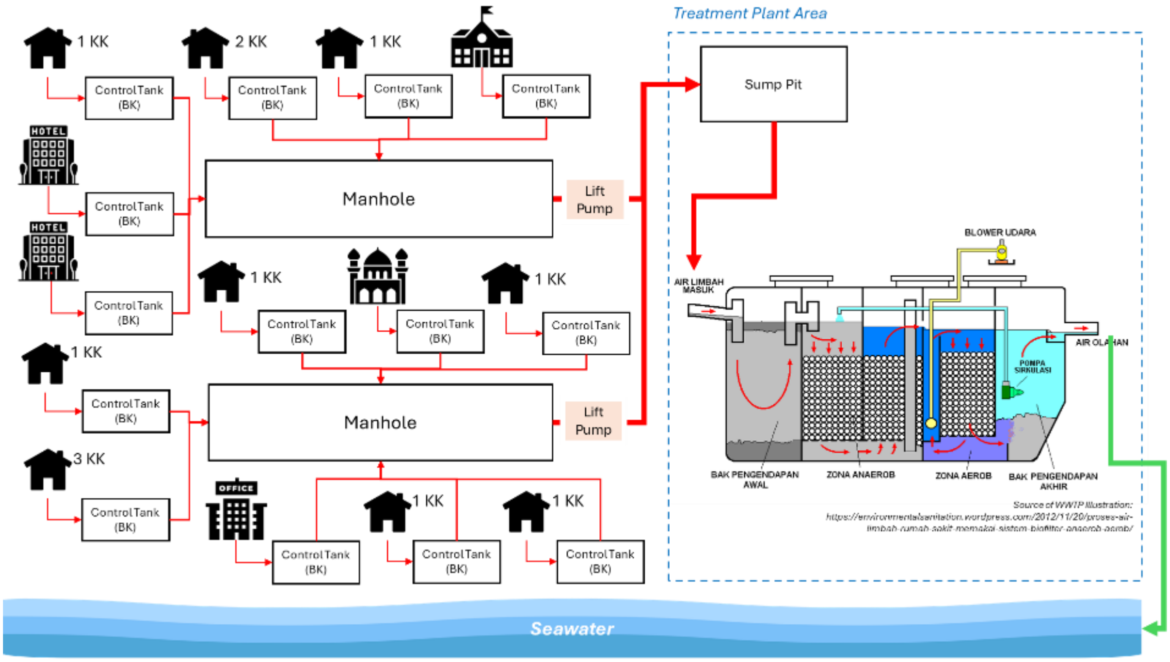


Figure 3. Flow chart of DWM system in Tidung Besar Island, Seribu Islands, Jakarta, Indonesia (Source: Personal visualisation based on research results 2025)

The four WWTP collectively have a total design capacity of 650 m^3/day, currently serving 831 house connections ("*sambungan rumah*"/SR). The capacities and service coverages of each WWTP are as follows: east (150 m^3/day; 204 SRs), north (200 m^3/day; 155 SRs), west (200 m^3/day; 449 SRs), and south (100 m^3/day; 23 SRs). From an institutional perspective, the system is managed by the Water Resources Agency of DKI Jakarta Province through its Seribu Islands Water Resources Sub-Agency, which oversees operation, maintenance, and monitoring activities. Based on standard design practices, the ratio between treatment capacity and house connections can be estimated from domestic wastewater generation rates and household size. Domestic wastewater production typically ranges from 100-200 L/person/day (Tchobanoglous *et al.* 2014; Badan Standardisasi Nasional (BSN) 2017).

Regarding Seribu Islands's average household size of 3.4 persons/household (Jakarta Provincial Population and Civil Registration Agency 2025), each house connection contributes approximately 0.34-0.68 m^3/day. Thus, a WWTP with a nominal capacity of 200 m^3/day (north and west zones) can theoretically serve 290-590 households, depending on water use and infiltration factors. This estimation aligns with common design practices in small-scale wastewater systems, where empirical adjustments accommodate variability in inflow, infiltration, and service expansion (Tchobanoglous *et al.* 2014). Notably, a local government news report quotes managers stating that planned plants will provide 150 m^3/day for south zone and 200 m^3/day for north zone (Surapati and Suparni 2016), implying 0.5 m^3/house/day (≈147 L/person/day at 3.4 persons/house). It means that the maximum service capacity reaches twice the nominal capacity is aligns with the technical range above and corresponds roughly to a mid-range per-capita assumption. Accordingly, service targets for the study area are set at 300 SR (east), 400 SR (north), 400 SR (west), and 200 SR (south). Based on these criteria, the West Zone WWTP has already exceeded its service capacity, with 449 SRs connected in 2025, equivalent to 112% of the designated maximum (**Figure 4**). Compared to the initial condition in 2016/2017, the number of SRs in the West Zone has increased significantly over the past decade. The East Zone also shows relatively high utilization at 68% of its maximum capacity, whereas the South Zone remains underutilized with limited additional connections (**Figure 4**).

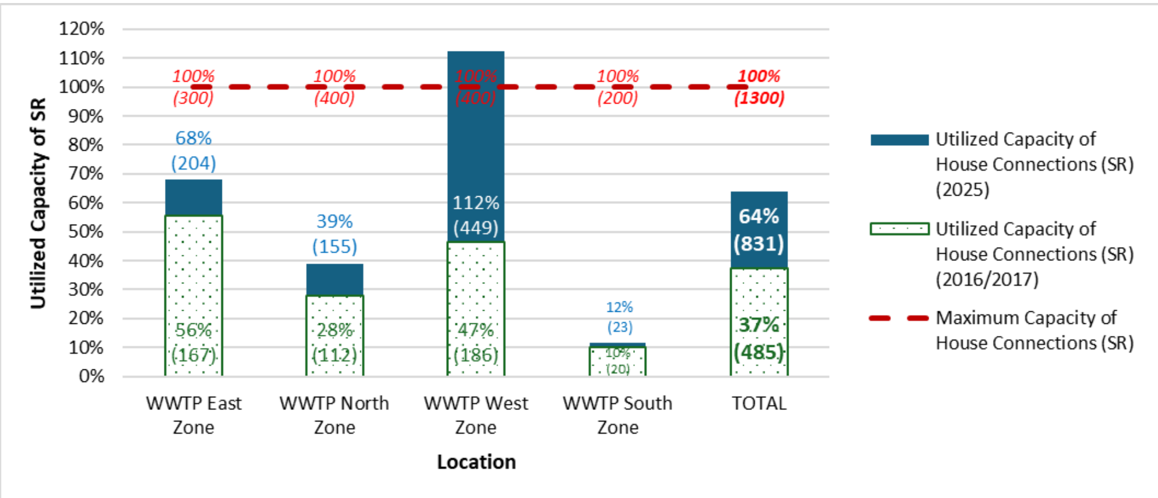


Figure 4. Evaluation of WWTP capacity based on the number of house connection (SR)

(Source: Data analysis and personal visualisation by author (2025))

Despite the established infrastructure, several technical challenges have been identified. Critical equipment failures include non-functional flow meters and inoperative recirculation units at WWTP installations, preventing accurate load measurement and compromising treatment efficiency. The pipe network experiences periodic clogging from user-generated solid waste disposal, and manholes occasionally flood during high rainfall or tides, raising aesthetic and safety concerns. In service coverage side, it is also persists incomplete due to residents' reluctance, limited awareness, and landowner access restrictions. From an institutional perspective, WWTP monitoring is conducted only annually, substantially below the monthly frequency required by PermenLHK No. 5/2021, Article 103 paragraph (2) (Minister of Environment and Forestry 2021). Weak managerial follow-up to monitoring results and limited operator understanding of system principles further constrain operational effectiveness. In addition, user awareness and maintenance of control tank (BK) by user remain inadequate, contributing to system performance issues.

Regarding effluent quality standards, the institutional framework primarily refers to the Regulation of the Minister of Environment and Forestry No. P.68/2016 on Domestic Wastewater Quality Standard (Minister of Environment and Forestry 2016), which focuses on wastewater characteristics for operational management. However, for a more comprehensive environmental assessment beyond the system's internal performance and consider its receiving environment, effluent quality was evaluated against three national regulatory references: (1) Regulation of the Minister of Environment and Forestry No. P.68/2016 (Minister of Environment and Forestry 2016); (2) Government Regulation No. 22/2021 on Environmental Protection and Management - Seawater Quality Standard for Maritime Tourism (President of the Republic of Indonesia 2021); and (3) Government Regulation No. 22/2021 on Environmental Protection and Management - Seawater Quality Standard for Marine Biota (President of the Republic of Indonesia 2021). Following common practice in environmental assessment studies in Indonesia, the strictest threshold value for each parameter across these three references was adopted as the reference standard, ensuring the most stringent environmental protection criteria. This approach provides a robust basis for evaluating the environmental performance of the system, as presented in the following subsection.

3.1.2. Environmental aspect

The environmental performance of the DWM system was evaluated based on effluent quality compliance with the reference standards described above. According to three years of WWTP monitoring data (Seribu Islands Water Resources Sub-Agency 2024), four parameters remained non-compliant with the applicable quality standards (QS) despite treatment (*italic text* on the outlet column of **Table 1**). Biochemical Oxygen Demand (BOD) and oil and grease exceeded the QS by approximately 2-5 times (QS = 10 mg/L) and 2-6 times (QS = 1 mg/L), respectively. More critically, ammonia and total coliform exhibited substantially higher exceedances, reaching 72-163 times (QS = 0.02 mg/L) and 26-137 times (QS = 1,000 MPN/100 mL), respectively. These results are consistent with the characteristics of domestic wastewater, which typically contains high concentrations of organic matter, fats, oils, grease (Huang *et al.* 2010; Parwin and Paul 2019), and proteins (Huang *et al.* 2010), along with coliform bacteria indicative of fecal contamination.

The persistent non-compliance of these parameters, particularly the extreme exceedances in ammonia and total coliform levels, indicates that the current anaerobic-aerobic treatment configuration may be insufficient to achieve the stringent quality standards. The non-compliance is compounded by several operational factors identified in the technical assessment. The inoperative recirculation units limit microbial biomass maintenance and wastewater dilution, both critical for treatment efficiency (Tchobanoglous *et al.* 2014; Santín *et al.* 2020). Infrequent monitoring (annual rather than monthly) allows performance degradation to accumulate undetected. BOD and oil and grease exceedances also suggest inadequate source control from poor BK maintenance practices. These findings reveal potential limitations in treatment process design and operational conditions that prevent adequate contaminant removal. While environmental performance metrics reveal significant technical challenges, the system's overall sustainability also depends on community acceptance and social dimensions, which are examined in the following subsection.

Table 1. Tidung Besar Island WWTP monitoring data during 2022-2024.

No.	Parameter	Unit	Strictest Quality Standard (QS)[a]	Average values							
				East zone		North zone		West zone		South zone	
				Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
1	pH	-	7-8.5	7.1	7.4	7.0	7.3	7.1	7.3	7.2	7.7
2	BOD_5	mg/L	10	*196*	*43*	*149*	*24*	*163*	*48*	*123*	*20*
3	COD	mg/L	100	*259*	60	*199*	34	*214*	67	*164*	30
4	TSS	mg/L	20	18	10	*22*	11	18	10	*23*	13
5	Oil and grease	mg/L	1	*8*	*6*	*8*	*5*	*8*	*5*	*7*	*2*
6	Ammonia	mg/L	0.02	*22*	*3*	*16*	*2*	*16*	*2*	*19*	*1*
7	Total coliform	MPN/100 mL	1,000	*203,233*	*54,810*	*176,842*	*83,217*	*193,067*	*136,942*	*119,335*	*25,779*
8	Discharge	m^3/s	-	0.0006	0.0008	0.0006	0.0007	0.0010	0.0011	0.0004	0.0008

Source: Primary data from Seribu Islands Water Resources Sub-Agency (Seribu Islands Water Resources Sub-Agency 2024) and Data analysis by author (2025)

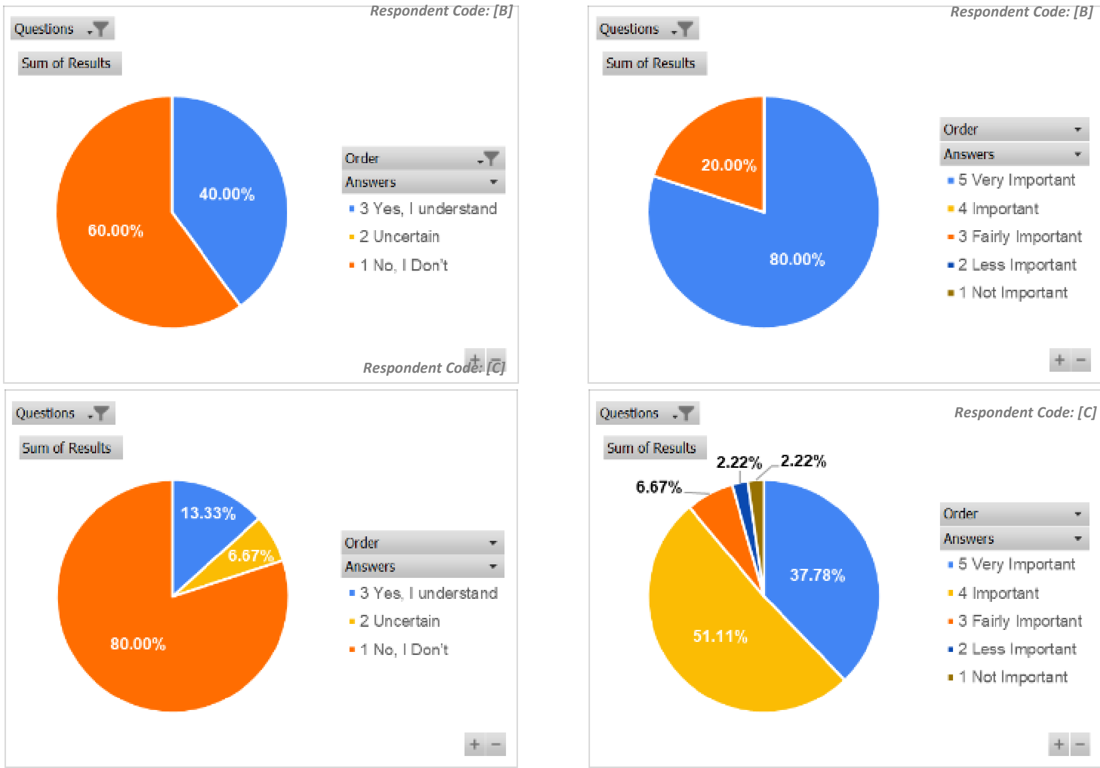
[a]Strictest quality standard (QS) refers to the most stringent threshold for each parameter, selected from among the following (3) three references:

(1) Regulation of the Minister of Environment and Forestry No P.68 Year 2016 on Domestic Wastewater Quality Standard (App. I. Domestic Wastewater Quality Standard) (Minister of Environment and Forestry 2016)
(2) Government Regulation No 22 of 2021 on the Implementation of Environmental Protection and Management (App. VIII. Seawater Quality Standard for Maritime Tourism) (President of the Republic of Indonesia 2021)
(3) Government Regulation No 22 of 2021 on the Implementation of Environmental Protection and Management (App. VIII. Seawater Quality Standard for Marine Biota) (President of the Republic of Indonesia 2021)

3.1.3. Social aspect

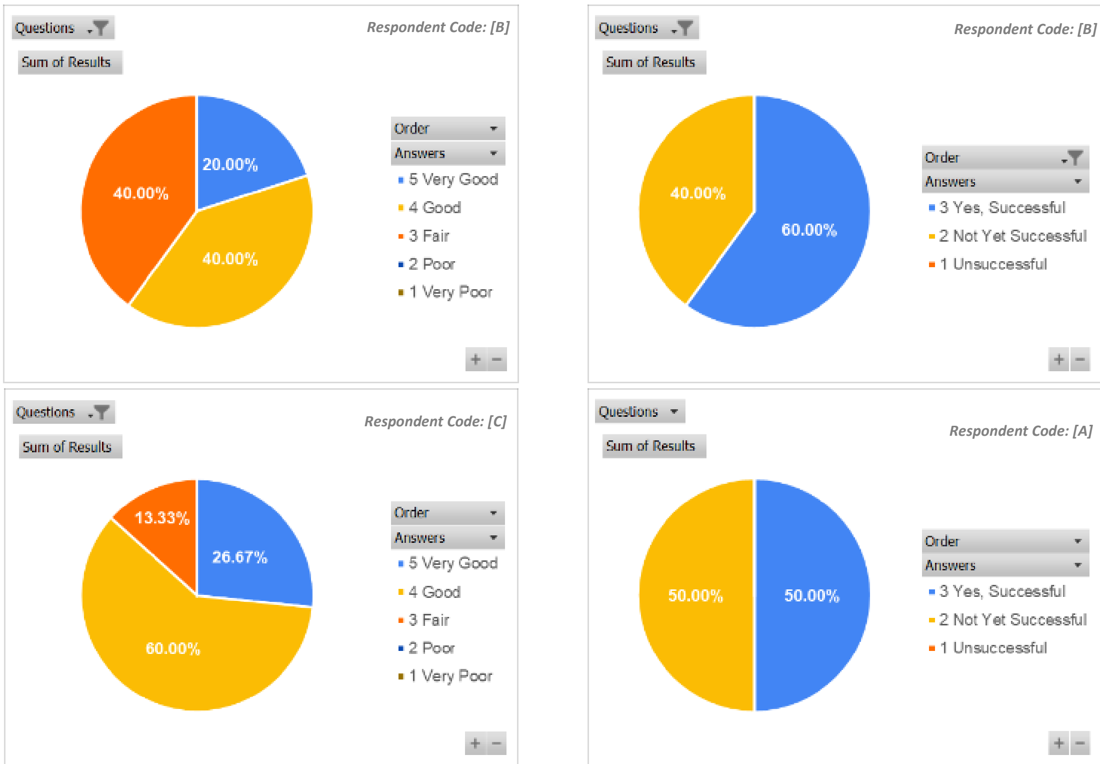
The social dimension of DWM implementation reveals an interesting paradox between community knowledge and attitudes. The understanding of DWM among the residents and local community leaders remains relatively low, with over 60% not knowing or understanding what domestic wastewater is (**Figure 5a**). However, despite this limited technical understanding, the majority (over 80%) considered DWM to be important to very important is (**Figure 5b**). This tendency is likely shaped by their direct experience with the DWM systems that have been operational on the island since 2016, which has provided tangible benefits even without comprehensive technical knowledge.

Community satisfaction with the overall performance of DWM was generally positive, with the most dominant response categorized as "good" (**Figure 5c**). This favourable perception aligns with stakeholder assessments, where most community leaders and approximately half of the WWTP managers perceived the system as successful (**Figure 5d**). The relatively high social acceptance and satisfaction levels, despite limited technical understanding and the environmental challenges, suggest that the community primarily evaluates system performance based on visible improvements and service availability.



Understanding of domestic wastewater
(a)

Importance of DWM
(b)



DWM performance
(c)

DWM success
(d)

Figure 5. Research questionnaire results.

However, this limited understanding manifests in behavioral challenges affecting system performance. Users' awareness and maintenance of control tanks (BK) remain inadequate, with irregular cleaning and poor upkeep. Improper solid waste disposal into the system causes pipe network clogging. There are also challenges from residents to expand connections and achieve complete service coverage due to misunderstandings about liquid waste management and, in some cases, landowners' refusal to provide network access. These behavioural factors indicate that while overall satisfaction is high, enhanced community education is needed to improve user practices and achieve complete service coverage. This social acceptance is crucial for long-term sustainability, as community support influences maintenance compliance, willingness to pay for services, and opportunities for future improvement.

3.2. Discussion

The multi-aspect assessment reveals a critical paradox that Tidung Besar Island's DWM system demonstrates strong social acceptance and established infrastructure yet faces severe environmental challenge and institutional capacity gaps. This contributes to limited research on small island wastewater management context, where communities face unique challenges of poor sewerage systems, financial constraints, inadequate managerial training, and geographic isolation (Willmott and Graci 2016; Prost-Boucle *et al.* 2023; SMILO 2023). While four WWTPs serving 831 connections represent significant achievement, the West Zone's 112% capacity exceedance, persistent equipment failures (flow meters, recirculation units), and annual rather than required monthly monitoring indicate fundamental institutional weaknesses. Similar capacity constraints have been documented in island contexts where tourism-dependent economies strain infrastructure and sustainable resource management proves particularly challenging (Willmott and Graci 2016; Rodríguez-Alcántara *et al.* 2024).

The severe non-compliance that is ammonia (72-163 times the QS) and total coliform (26-137 times the QS) indicates treatment inadequacies beyond typical domestic wastewater characteristics. While anaerobic-aerobic systems effectively remove organic matter, achieving stringent ammonia and pathogen removal often requires operational optimization or tertiary treatment (Kassab *et al.* 2010; Englande *et al.* 2015). The non-functional recirculation unit contributes to these deficiencies, as recirculation it is critical for maintaining adequate microbial biomass in the aerobic stage and for diluting incoming high-strength wastewater, both essential for treatment efficiency (Tchobanoglous *et al.* 2014; Englande *et al.* 2015; Santín *et al.* 2020). This situation mirrors Pacific islands where inadequate wastewater treatment has caused serious environmental and health problems due to contamination of water supplies and damage to natural resources (Rouse 2015; Nelson *et al.* 2024). Given the high ecological sensitivity of coastal waters, applying the strictest national standards (P.68/2016; PP 22/2021) represents methodological rigor appropriate for marine tourism areas and supports the protection of marine ecosystems.

Most striking is the paradox between environmental challenges and high social acceptance. Despite severe non-compliance and 60% not understanding domestic wastewater, over 80% considered DWM important with predominantly "good" satisfaction. Communities assess visible improvements (eliminated open sewers, service availability) rather than invisible water quality parameters. This pattern is common not only in small-island contexts where limited environmental literacy and lack of monitoring transparency constrain communities' capacity for critical evaluation (Domnech and Saurí 2010; Jones *et al.* 2011; United Nations 2017). Research shows those with higher environmental concern have more positive attitudes toward wastewater treatment (Gómez-Román *et al.* 2021; Gómez-Román *et al.* 2024), suggesting awareness-raising could transform passive acceptance into active improvement demand. That most of local leaders and half of WWTP managers also perceive the system as successful despite non-compliance indicates normalization of inadequate performance, reflecting insufficient monitoring data access, insufficient technical or environmental literacy, and institutional weaknesses that remains prioritizing continuity over optimization. This perception of 'success' is inherently biased, reflecting assessments that prioritize system functionality over effluent quality.

The multi-aspect assessment reveals that challenges across technical, institutional, environmental, and social dimensions are deeply interconnected, creating a complex web of causality that requires integrated solutions. West Zone overcapacity results from population growth outpacing infrastructure planning and service expansion efforts without regard to carrying capacity, compromising treatment efficiency. Pipe blockages stem from inappropriate user disposal due to limited awareness within perceived system success. The persistence of essential equipment from a complex maintenance budgeting process prevents accurate measurement and treatment effectivity, undermining capacity and quality management while remaining invisible to users. This demonstrates isolated technical fixes will fail without simultaneous institutional strengthening and social engagement. A holistic approach that recognises sociological factors, including community participation, public engagement, and social perceptions, is required and is expected to bring improvements in wastewater management practice (Saad *et al.* 2017).

Immediate interventions must address West Zone capacity through expansion or redistribution, repair essential equipment, increase disinfection intensity, and establish monthly monitoring. Medium-term improvements should explore advanced technology in WWTPs, such as ozonation and other advanced oxidation processes (AOPs) for enhanced pathogen and ammonium removal, UV-irradiation systems for disinfection and polishing, membrane filtration (UF/NF/RO or membrane-bioreactor hybrids) to achieve high-quality effluent, and nitrogen-specialised processes (e.g., Anammox or SHARON) to address excessive ammonia loads. Such technologies have been demonstrated in recent literature to markedly increase removal of pathogens, organic and inorganic nitrogen species, and recalcitrant contaminants under challenging conditions (Bray *et al.* 2021; Clem and Mendonça 2022; Zagklis and Bampos 2022; Zahmatkesh *et al.* 2022; Fernandes *et al.* 2024; Parulekar *et al.* 2024; Ugwuanyi *et al.* 2024). Careful consideration must apply in the selection of the advanced technologies relating the constraints typical of small islands and another inherent challenges, such as geographic isolation, higher financial requirements for operation and maintenance, and limited local capacity in terms of energy availability and operator technical skills.

Beyond technical measures, institutional protocols must ensure monitoring data translates into corrective actions, supported by operator training addressing system principles and ecological functions. At a broader policy level, the institutional framework should formalize multi-reference quality standards for island contexts, aligning operational targets with ecological protection. Equally important, community education through local leaders should emphasize connections between DWM performance and tangible interests (tourism quality, fisheries, public health).

Portraying wastewater treatment as a community initiative with pro-environmental social identity framing generates more positive and fewer negative emotions, positively influencing acceptance (Gómez-Román *et al.* 2024). These measures will foster the community's sense of belonging, which has been proven to increase participation in conservation (García-Llorente *et al.* 2012). To sustain these efforts, budget allocation must prioritize integrated maintenance, monitoring, training, and education.

This study addresses knowledge gaps in small island wastewater management where this such research remains scarce. The paradox that social acceptance despite environmental challenges may be common where communities lack critical evaluation capacity, suggests acceptance alone is insufficient for sustainability or success assessment. The multi-reference quality standard approach provides a model for island contexts with marine ecosystem dependencies. The interconnected challenge framework linking technical, institutional, environmental, and social aspects offers conceptual tools for integrated management approaches. For Tidung Besar specifically and small islands globally, transforming passive acceptance into sustainable performance requires simultaneous technical upgrades, institutional strengthening, and strategic social engagement protecting human health, marine ecosystems, and tourism-dependent livelihoods.

4. CONCLUSION

This assessment reveals Tidung Besar Island's DWM system faces critical sustainability challenges despite infrastructure achievement and community acceptance. Severe environmental non-compliance (ammonia and coliform exceeding standards up to 163 and 137 times), institutional capacity gaps, and technical constraints are the challenges in question. The paradox of high satisfaction despite poor environmental performance demonstrates that sustainable small island domestic wastewater management requires integrated solutions addressing interconnected technical, institutional, environmental, and social dimensions simultaneously. The study contributes methodological value of multi-reference quality standards for island with marine ecosystem dependencies contexts and an interconnected challenge framework applicable beyond this case and offering transferable lessons for small islands globally balancing development, tourism, and environmental protection.

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