

















## Drinking Water Supply Strategies for Archipelagic States: Scale-Constrained Systems and Off-Grid Solutions from Small Islands in Indonesia

Nicco Plamonia<sup>1\*</sup>, Rizki Arizal Purnama<sup>1</sup>, Yeni Novitasari<sup>2</sup>, Elshedeveka Rosya<sup>3</sup>, Heru Mulyono<sup>4</sup>, Rizki Firmansyah<sup>5</sup>, Wahyu Purwanta<sup>1</sup>, Dwi Budiyanto Trisnoharjono<sup>6</sup>, Ahmad Nuridha<sup>6</sup>, Indri Mardiyana<sup>7</sup>, Suwarti Wati<sup>7</sup>, Agus Setiawan<sup>6</sup>, Susilo Raharjo<sup>7</sup>, Revina Devitani Putri<sup>6</sup>

<sup>1</sup> Research Center for Environmental and Clean Technologies, National Research and Innovation Agency (BRIN), South Tangerang 15314, Indonesia

<sup>2</sup> Research Center for Mineral Technology, National Research and Innovation Agency (BRIN), South Tangerang 15314, Indonesia

<sup>3</sup> Research Center for Sustainable Industrial and Manufacturing Systems, National Research and Innovation Agency (BRIN), South Tangerang 15314, Indonesia

<sup>4</sup> Research Center for Behavioral and Circular Economics, National Research and Innovation Agency (BRIN), South Tangerang 15314, Indonesia

<sup>5</sup> Directorate for Policy Formulation of Research, Technology, and Innovation, National Research and Innovation Agency (BRIN), South Tangerang 15314, Indonesia

<sup>6</sup> Research Center for Equipment Manufacturing Technology, Organization for Energy and Manufacturing, National Research and Innovation Agency (BRIN), South Tangerang 15314, Indonesia

<sup>7</sup> Research Center for Process Technology, Organization for Energy and Manufacturing, National Research and Innovation Agency (BRIN), South Tangerang 15314, Indonesia

Corresponding Author Email: [nicco.plamonia@brin.go.id](mailto:nicco.plamonia@brin.go.id)

Copyright: ©2026 The authors. This article is published by IETA and is licensed under the CC BY 4.0 license (<http://creativecommons.org/licenses/by/4.0/>).

<https://doi.org/10.18280/ijstdp.210508>

### ABSTRACT

**Received:** 4 March 2026

**Revised:** 19 May 2026

**Accepted:** 26 May 2026

**Available online:** 31 May 2026

#### Keywords:

*small islands, drinking water supply, off-grid systems, scale mismatch, archipelagic states*

Small inhabited islands in archipelagic states experience persistent drinking water insecurity driven by structural hydrogeological constraints, extreme scale limitations, and institutional mismatch with centralized utility systems. In Indonesia, thousands of micro-islands host long-established communities but lack permanent freshwater due to limited catchment areas, saline groundwater intrusion, and high evapotranspiration. Despite small populations, households face disproportionately high water costs through reliance on rainwater harvesting, purchased water, and transported supplies. This study analyses drinking water provision across very small inhabited islands in Indonesia using a comparative mixed-evidence approach centered on secondary datasets with limited field verification. Physical island characteristics, household water access conditions, cost structures, and governance arrangements are comparatively assessed across islands from Indonesia's five major island regions. All micro-island cases ( $\leq 200$  inhabitants) remain below  $15 \text{ m}^3/\text{day}$ , while two comparator islands exceed this threshold. These demand levels remain substantially below the operational scale typically associated with centralized water utility systems. Household water prices range from Rp300–600 per liter, equivalent to 50–200 times mainland tariffs, with water expenditures accounting for approximately 10–20% of monthly household spending. Indicative capital–operational cost analysis shows that although per-capita capital costs of micro-scale systems are relatively high, total investment requirements remain modest in absolute terms, while operating costs remain lower than prevailing purchased-water prices. Across all cases, centralized on-grid systems and population relocation are empirically unviable. Scale-appropriate off-grid systems—including micro reverse osmosis units, rainwater harvesting with basic disinfection, and hybrid configurations—emerge as the most technically feasible, economically rational, and socially equitable approaches for small-island drinking water provision. The findings indicate that drinking water insecurity on very small inhabited islands is fundamentally a structural and scale-sensitive problem requiring island-category-based planning, decentralized system design, and sustained public investment rather than uniform utility expansion.

## 1. INTRODUCTION

Indonesia comprises approximately 17,000–17,500 islands,

of which about 5,000–6,000 are permanently inhabited [1, 2]. Most inhabited islands fall into the micro and small categories, characterized by limited land area, narrow catchments,

shallow aquifers, and high vulnerability to seawater intrusion. Empirical evidence from Miangas Island shows that freshwater availability is constrained primarily by hydrogeological conditions, particularly high evapotranspiration and extremely limited catchment capacity, rather than by rainfall levels. Despite these constraints and relatively small populations, many of these islands sustain long-established livelihood systems, particularly small-scale fisheries, making water security both an economic and equity concern.

Within Indonesia's national drinking water system, centralized utility services remain concentrated in mainland and urban growth centres, leaving most small islands outside piped network coverage. In practice, communities rely on rainwater harvesting, shallow saline groundwater, transported water, or high-cost bottled water. Structural limitations—limited raw water sources, geographic fragmentation, and insufficient demand to achieve economies of scale—restrict the feasibility of conventional centralized systems.

Approximately 2,000–3,000 islands are inhabited by fewer than 200 people, while only 100–200 islands exceed 10,000 inhabitants [1, 2]. Based on this distribution, micro islands

cumulatively host an estimated 0.2–0.6 million people, and small islands (200–1,000 inhabitants) approximately 0.6–1.6 million people. In total, around 0.8–2.2 million people reside on micro and small islands, representing a demographically modest yet nationally significant population segment that falls structurally outside the technical and economic design envelope of centralized utility-based systems (see Table 1).

Although decentralized options—such as rainwater harvesting and micro-scale desalination (< 5 m<sup>3</sup>/day)—are generally more suitable for settlements below 300–500 inhabitants [3–6], a comprehensive framework integrating demographic thresholds, hydrogeological constraints, and institutional feasibility remains underdeveloped.

Addressing this gap, this study develops a scale-sensitive drinking water supply framework for very small inhabited islands in Indonesia by identifying structural freshwater constraints, examining demographic and institutional limits of centralized utilities, and formulating governance and technological pathways for equitable off-grid provision. In doing so, the study repositions island water planning from infrastructure expansion toward threshold-based, scale-appropriate system design in archipelagic states.

**Table 1.** Distribution of Indonesian islands by population size and raw water availability constraints

Island Category	Population	Estimated Number of Islands	Key Characteristics	Technical Implication
Uninhabited	0	± 11,000–11,500	No permanent settlement	No water demand
Micro	≤ 200	± 2,000–3,000	Very small settlements, no permanent freshwater	No local raw water
Small	200–1,000	± 1,500–2,000	Limited groundwater, high intrusion	Severely limited raw water
Medium	1,000–10,000	± 600–800	Permanent settlements, limited services	Limited local sources
Large	> 10,000	± 100–200	Urban-like islands, coastal towns	Regional raw water available

## 2. MATERIAL AND METHOD

The materials and methods used in this study are organized into eight interrelated subsections. Section 2.1 outlines the research design and analytical approach; Section 2.2 presents the analytical perspective; Section 2.3 describes case selection and study areas; Section 2.4 details data sources and materials; Section 2.5 defines analytical dimensions and measurement; Section 2.6 introduces the evaluative framework; Section 2.7 explains the analytical methods; and Section 2.8 presents the comparative analytical strategy. Together, these subsections establish a coherent framework for comparative assessment of drinking water conditions and scale-appropriate supply strategies on very small inhabited islands.

### 2.1 Research design and analytical approach

This study adopts a descriptive–analytical design based on secondary policy [7, 8] and infrastructure data verification to examine drinking water access challenges on very small inhabited islands and to identify scale-appropriate supply strategies. The analysis applies comparative pattern assessment and cross-case comparison to examine recurring relationships between island physical and demographic conditions, freshwater limitations, household water access conditions, and drinking water supply strategies. The study emphasizes comparative interpretation and policy relevance rather than formal statistical inference [9–11].

### 2.2 Analytical perspective

This study examines drinking water provision on very small islands through a comparative policy–infrastructure perspective focused on structural constraints, limited demand scale, and household water access conditions. Rather than testing a formal causal theory, the analysis identifies recurring cross-case patterns linking hydrogeological limitations, small population size, high water costs, and dependence on non-networked water supply systems. The framework is used to assess the suitability of different drinking water strategies under small-island conditions.

#### 2.2.1 Structural hydrogeological and spatial constraints

Very small islands are characterized by limited land area, narrow catchments, shallow aquifers, high evapotranspiration rates, and strong vulnerability to seawater intrusion [12–14]. As a result, freshwater scarcity in these environments is primarily hydrogeological rather than meteorological.

These conditions restrict the availability of reliable freshwater sources and increase dependence on rainwater harvesting, transported water, or small-scale desalination systems. Geographic fragmentation and low population density also limit the feasibility of centralized network-based water supply systems [3].

Small islands are widely recognized as highly vulnerable freshwater environments because groundwater resources are typically limited to thin freshwater lenses that are sensitive to

seawater intrusion, prolonged drought, and climate variability. These hydrogeological limitations have been documented across Pacific and Caribbean island systems and are considered one of the principal constraints to long-term water security in island environments [13, 15-17].

### 2.2.2 Scale mismatch in centralized utility design

Centralized water supply systems are generally designed for larger and more concentrated populations that can support network infrastructure and economies of scale. Centralized water systems generally operate more efficiently when serving larger and spatially concentrated populations.

However, in very small island settlements, demand volumes are often too low to sustain conventional utility-based systems efficiently. Under these conditions, infrastructure costs remain high relative to output, while geographic isolation further constrains operational feasibility.

### 2.2.3 Water costs and demand scale

Water supply systems on small islands frequently operate at very low production volumes. While decentralized systems may function under small-demand conditions, centralized utility systems generally require larger demand aggregation to distribute infrastructure and operational costs efficiently [18, 19]. In many very small island settlements, limited freshwater availability and low demand magnitude are associated with relatively high unit water costs compared with mainland systems.

Previous studies have shown that water supply systems serving small and geographically isolated populations frequently experience diseconomies of scale, resulting in higher unit production costs and reduced operational efficiency compared with mainland systems. Under such conditions, decentralized and modular systems often provide more economically viable service arrangements [20-22].

### 2.2.4 Household water costs and socio-economic implications

Households on very small islands commonly rely on purchased water, transported water, or rainwater harvesting systems.

These conditions are associated with relatively high household water expenditures compared with mainland utility users [23, 24].

High water prices may reduce affordability and increase household vulnerability, particularly in low-income island communities. Household water access patterns, therefore, provide an important indicator for evaluating the economic implications of small-island drinking water systems.

### 2.2.5 Appropriate drinking water strategies

The recurring conditions observed across very small islands indicate that drinking water provision requires approaches compatible with local physical and demographic conditions. Uniform infrastructure models designed for mainland or urban systems may not align with the operational realities of very small islands.

Under these conditions, decentralized and scale-appropriate systems—including rainwater harvesting, micro-scale desalination, and hybrid off-grid configurations—represent important alternatives for improving drinking water access in archipelagic settings.

A growing body of evidence suggests that rainwater harvesting, small-scale desalination, and hybrid water supply systems offer practical and resilient solutions for remote island

communities where conventional utility expansion is technically difficult and economically inefficient. Such approaches have been increasingly promoted as key components of water security strategies for Small Island Developing States (SIDS) and other archipelagic regions.

## 2.3 Case selection and study area

This study adopts a comparative case study approach to examine freshwater supply challenges on very small inhabited islands in Indonesia. The selected cases are intended to represent typical hydrogeological and socio-technical conditions faced by islands with limited population size, constrained natural freshwater resources, and the absence of formal water utility services. Emphasis is placed on ensuring both geographic representativeness and data availability to support cross-regional analysis.

### 2.3.1 Selection criteria

Fifteen very small inhabited islands were selected as illustrative case studies based on the following criteria: (1) small permanent population of fifteen inhabited islands was selected, consisting of thirteen micro islands ( $\leq 200$  inhabitants) and two upper-bound comparator islands representing larger small-island conditions. Comparator islands were included to assess how water demand and system feasibility evolve beyond the micro-island threshold; (2) absence of centralized water utilities-based supply; (3) geographic representation of Indonesia's five major island groups; (4) availability of secondary data from government reports or previous studies. These criteria ensure that the selected islands share comparable scale-related constraints while capturing regional variability in physical and institutional settings.

Population ranges are based on regional statistical records and secondary sources. Permanent freshwater availability refers to the presence of reliable, non-saline surface or groundwater sources. PDAM responsibility is administrative; none of the islands are served by operational on-grid utility systems. For each selected island, data were compiled on geographic location, population range, freshwater availability, dominant household water source, and administrative responsibility for drinking water provision. These variables were used to operationalize structural constraints and household water access patterns at the island level.

### 2.3.2 Case distribution

Based on the above criteria, the selected islands are evenly distributed across Indonesia's five major island groups to avoid regional bias and to reflect diverse environmental and demographic conditions. The spatial distribution of the fifteen case study islands across Indonesia is presented in Figure 1, while their demographic and water access characteristics are summarized in Table 2.

## 2.4 Data sources and materials

This study employs a combination of secondary and limited primary data to ensure both breadth and contextual depth in analysing freshwater supply conditions on very small islands. Secondary data provide national-scale consistency, while primary data from selected locations offer field-based validation of documented conditions.

### 2.4.1 Primary field verification, sampling design, and

measurement period

This study is primarily based on secondary national datasets (BIG, BPS, BRIN, PUPR, 2019–2024); limited field verification was conducted between (1) July 2019–September 2019 (Sumatra cases); (2) August 2021–October 2021

(Sulawesi cases); (3) May 2023–July 2023 (follow-up validation and price confirmation).

These visits were conducted to validate household water consumption levels, price structures, and seasonal supply patterns documented in secondary sources.



**Figure 1.** Spatial distribution of fifteen small inhabited islands across five major island regions of Indonesia

**Table 2.** Distribution of case study islands

Five Major Island Regions	Island	Approx. Latitude	Approx. Longitude	Province	Population Estimate	Dominant Water Source	Responsible Water Utility (PDAM)
Sumatra	Tailana	2.229148° N	97.222697° E	Aceh	200–250	Rainwater harvesting	PDAM Aceh Singkil Regency
	Salah Namu	3.342222° N	99.722778° E	North Sumatra	~ 100–300 (est.)	Transported water	PDAM Langkat Regency
	Berhala Kecil	−0.857462° S	104.405733° E	Jambi	~ 80–250 (est.)	Rainwater harvesting	PDAM East Tanjung Jabung Regency
Java	Pamujan Kecil	−5.964167° S	106.193056° E	Banten	~ 90–180 (est.)	Purchased water	PDAM Serang Regency
	Bidadari	−7.250315° S	113.726014° E	East Java	~ 80–200 (est.)	Brackish shallow wells	PDAM Sumenep Regency
	Gili Raja Kecil	−7.218441° S	113.784107° E	East Java	~ 90–190 (est.)	Rainwater harvesting	PDAM Sumenep Regency
Kalimantan	Nunukan Island	4.053292° N	117.666724° E	North Kalimantan	~ 80–170 (est.)	Purchased water	PDAM Nunukan Regency
	Maratua Kecil	2.211147° N	118.622775° E	East Kalimantan	~ 70–150 (est.)	Rainwater harvesting	PDAM Berau Regency
	Pulau Manti	−3.519212° N	116.376819° E	South Kalimantan	~ 60–140 (est.)	Transported water	PDAM Kotabaru Regency
Sulawesi	Langkai	−5.031662° S	119.094481° E	South Sulawesi	~ 90–150 (est.)	Rainwater harvesting	PDAM Makassar City
	Kulambang	−4.786100° S	119.431138° E	South Sulawesi	~ 80–160 (est.)	Brackish shallow wells	PDAM Pangkep Regency
	Gangga	−1.767410° S	125.054326° E	North Sulawesi	~ 80–160 (est.)	Purchased water	PDAM North Minahasa Regency
Papua & Maluku	Owi	−1.241729° N	136.207663° E	Papua	300–450	Rainwater harvesting	PDAM Biak Numfor
	Ur	−0.847911° S	132.536052° E	Maluku	745–4783	Transported water	PDAM Kota Tual
	Numfor Kecil	−1.005270° S	134.848952° E	Papua	~ 100–180 (est.)	Shallow wells	PDAM Biak Numfor Regency

**Sampling Design.** Across the 15 islands, household interviews were conducted using structured questionnaires. Sampling was purposive but proportionally distributed to reflect settlement size. Total estimated households across 15 islands: ~420–480 households. Sampled households: (1) 8–15 households per island; (2) Total verified households: 132 households; (3) Estimated coverage: 25–32% of households on micro islands ( $\leq 200$  inhabitants). Household size assumptions (cross-checked with BPS 2019–2023 district data): Average household size: 4–5 persons per household.

**Consumption Measurement Method.** Water consumption data were collected using three complementary approaches: (1) Self-reported daily consumption (L/household/day); (2) Volumetric estimation based on container counts (20 L jerrycans; 200 L drums); and (3) Refill frequency tracking (per week). Since no island had functioning water meters, standardized per capita consumption (L/cap/day) was calculated as (see Eq. (1)):

$$L_{cap/day} = \frac{Q_h}{N_h} \quad (1)$$

where, (1)  $L_{cap/day}$  = per capita water consumption (L/capita/day); (2)  $Q_h$  = total household water consumption per day (L/day); (3)  $N_h$  = number of household members (persons).

Reported values were cross-checked against physical storage capacity observed during visits.

**Per Capita and Total Demand Calculation.** Standardized per capita consumption ( $L_{cap/day}$ ) was derived from household-level volumetric estimation. Total island-level water demand was then calculated using:

$$Q_d = \frac{P \times C_p}{1000} \quad (2)$$

where, (1)  $Q_d$  = total daily water demand ( $m^3/day$ ); (2)  $P$  = island population (persons); (3)  $C_p$  = per capita water consumption ( $L_{cap/day}$ ); (4) 1000 = conversion factor from liters to cubic meters ( $1 m^3 = 1000 L$ ). Population refers to the most recent district-level demographic estimate (2019–2023).

**Seasonal Framing.** Respondents were asked to distinguish between: (1) Wet season (November–April); (2) Dry season (May–October). All water demand values as presented later in the results section reflect: Dry-season effective consumption, representing the most constrained operational condition.

**Water Price Data Collection.** Water prices were documented during: (1) Field interviews (2019, 2021, 2023); (2) Vendor transaction observation; (3) District government records (2019–2024). Prices were standardized into: (1) Rp per liter; (2) Rp per  $m^3$  equivalent. Mainland PDAM tariffs used for comparison were taken from District tariff schedules (2022–2024).

**Scope of Water Demand Calculation.** Water demand calculations include: Household domestic use (drinking, cooking, washing, sanitation), and exclude: (1) Institutional demand (schools, mosques, public buildings); (2) Commercial demand (fish landing, ice production); (3) System losses (non-revenue water). Institutional demand was separately estimated (see Results section) but not included in per capita demand calculations.

#### 2.4.2 Secondary data sources

The study exclusively uses secondary data obtained from:

(1) National island inventories (Badan Informasi Geospasial-BIG); (2) Population statistics (BPS); (3) Technical reports from BRIN and the Ministry of Public Works and Housing (PUPR); (4) Peer-reviewed journal articles indexed in Scopus and Web of Science; (5) WHO guidelines on small drinking water systems. In addition, primary data were collected through field visits to several very small inhabited islands in Sumatra and Sulawesi. These visits provided qualitative and observational information on existing water sources, storage practices, and operational conditions, which were used to corroborate and contextualize the secondary data.

#### 2.4.3 Materials used

The materials and data inputs employed in this study are summarized in Table 3, including spatial datasets, technical reports, economic information, and policy documents relevant to small-island water supply systems.

**Table 3.** Materials and data inputs

Material	Description	Purpose
Island inventory datasets	Island size, location, population	Structural classification
Water supply reports	Existing water sources & systems	Access pattern analysis
Cost data	Water prices, capital expenditure, and operational expenditures	Comparative cost analysis
Policy documents	National & regional regulations	Policy synthesis

### 2.5 Analytical dimensions and measurement

This study applies a parsimonious analytical structure appropriate for comparative policy and infrastructure assessment. Analytical dimensions are defined to capture recurring physical, economic, and operational conditions affecting drinking water provision on very small inhabited islands. The framework focuses on structural conditions, household water access conditions, and drinking water access outcomes relevant to comparative evaluation.

#### 2.5.1 Structural conditions

Structural constraints of small islands are defined as natural and demographic conditions that inherently limit both the availability of raw freshwater resources and the technical-economic feasibility of centralized water supply systems. These constraints are considered exogenous and relatively fixed, particularly for very small inhabited islands (see Table 4).

#### 2.5.2 Household water access conditions

Household water access pattern is defined as the predominant strategies adopted by households to obtain freshwater in response to the structural constraints of small islands, including limitations in natural water availability and the absence of centralized water supply systems (see Table 5).

#### 2.5.3 Drinking water access conditions

The level of drinking water access is defined as the extent to which households on small islands achieve safe, affordable, and sustainable access to drinking water, reflecting service coverage, economic affordability, and system reliability (see Table 6).

**Table 4.** Operational indicators of structural constraints of small islands

No.	Indicator	Operational Description	Data Source
1	Island size and catchment limitation	Classification of islands based on land area and effective catchment capacity (small vs. very small islands)	National Island Inventories (BIG)
2	Groundwater availability	Presence, absence, or salinity condition of groundwater resources	BRIN–PUPR technical reports; peer-reviewed literature
3	Rainfall dependency	Degree of reliance on rainfall as the primary or sole freshwater source	BRIN–PUPR technical reports; peer-reviewed literature
4	Population size category	Population classification ( $\leq 200$ ; 200–1,000; 1,000–10,000; $> 10,000$ inhabitants)	BPS population data

**Table 5.** Operational indicators of household water access patterns

No.	Indicator	Operational Description	Data Sources
1	Dominant water source	Main source of water used by households (rainwater harvesting, purchased water, or transported water)	Published case studies; regional government reports
2	Relative water price	Household water cost relative to mainland utility tariffs (lower, comparable, or higher)	Published case studies; empirical findings from previous island water studies

**Table 6.** Operational indicators of drinking water access level

No.	Indicator	Operational Description	Data Sources
1	Access to safe drinking water	Percentage of households with access to drinking water meeting safety standards	Published case studies; regional government reports
2	Relative affordability	Household water expenditure as a proportion of total household income	Published case studies; empirical findings from island water studies
3	System reliability	Continuity of water availability across seasons (non-seasonal vs. seasonal access)	Published case studies; regional government reports

**Table 7.** Outcome indicators aligned with research objectives

Research Objective	Outcome Dimension	Output Indicator (Measurable)	Unit / Proxy Data	Relevance
Objective 1 Characterize structural constraints	Physical feasibility	Absolute daily water demand	m <sup>3</sup> /day ( $\leq 20$ –30 for micro islands)	Indicates demand scale condition
	Resource availability	Presence/absence of permanent freshwater	Binary (yes/no)	Indicates freshwater limitation
Objective 2 Examine utility limitations	Economic burden	Household water price ratio	Ratio vs mainland utility (50–200 $\times$ )	Indicates relative household burden
	Affordability	Share of water expenditure	% of household income (10–20%)	Indicates affordability condition
Objective 3 Develop scale-appropriate framework	Service reach	Coverage by utilities-based systems	% islands served ( $\approx 0\%$ for $\leq 200$ )	Indicates service limitation
	Access outcome	Share of households with safe water	% households	Main drinking water outcome
	System reliability	Non-seasonal availability	Months/year	Indicates operational continuity
	Sustainability	OPEX vs household ability to pay	Rp/m <sup>3</sup> vs income	Indicates sustainability consideration

**Table 8.** Evaluative criteria for assessing drinking water strategies on small islands

Criterion	Definition	Evaluation Question	Threshold / Reference
Technical viability	Compatibility with island physical conditions	Can the system operate without permanent freshwater?	Must function with seawater/rainwater only
Scale compatibility	Match between system capacity and demand	Is demand within minimum viable scale?	$\leq 30$ m <sup>3</sup> /day $\rightarrow$ off-grid only
Economic sustainability	Balance between CAPEX–OPEX and affordability	Is water cheaper than purchased water?	OPEX $<$ Rp20,000/m <sup>3</sup>
Equity of access	Fairness compared to mainland households	Does it reduce price ratio?	$< 10\times$ mainland tariff
Institutional fit	Alignment with operator capacity	Can it be run outside utilities?	Community/BUMDes feasible
Resilience	Climate and seasonal robustness	Can it operate during dry months?	$\geq 10$ –12 months/year

### 2.5.4 Outcome (Output indicators)

The outcome indicators aligned with the research objectives, translating key analytical dimensions into measurable variables. Table 7 clarifies how physical, economic, institutional, and access-related factors interact to explain drinking water outcomes on very small inhabited islands.

### 2.5.5 Evaluative criteria

To systematically assess the suitability of drinking water supply strategies for small islands, this study applies a set of evaluative criteria encompassing technical, economic, institutional, and social dimensions, as summarized in Table 8.

## 2.6 Evaluative framework

This study applies an evaluative framework to compare drinking water conditions and supply strategies across very small inhabited islands. The framework focuses on recurring structural characteristics, including freshwater availability, population scale, household water access conditions, and operational suitability of different supply systems. Rather than applying formal explanatory modelling, the framework is used to organize comparative assessment across cases and to evaluate the compatibility of centralized and decentralized drinking water approaches under small-island conditions. Table 9 maps key analytical dimensions to measurable indicators and evaluative criteria used throughout the study.

An evaluative structure is required to assess where and how policy intervention can effectively modify this pathway. Accordingly, the causal logic of the conceptual model is translated into an evaluative flow chart (see Table 9) and evaluative sequences, which serve as the analytical backbone for outcome assessment and policy comparison.

**Table 9.** Maps key analytical dimensions to measurable indicators and evaluative criteria used throughout the study

Analytical Dimension	Indicator	Evaluative Criterion
Structural constraints	Absence of freshwater	Technical viability
Household water conditions	Water price ratio	Economic sustainability
Socio-economic conditions	Water expenditure share	Affordability
Supply strategy	Technology selected	Scale compatibility
Drinking water outcome	Safe water access	Reliability & resilience

## 2.7 Analytical methods

This study applies a qualitative–comparative analytical approach consistent with its mixed-evidence design. The analysis focuses on identifying recurring structural patterns and policy-relevant implications across the selected islands rather than formal statistical inference. The analytical process consists of: (1) descriptive profiling of island physical and demographic conditions; (2) comparison of household water access conditions and freshwater limitations; (3) comparative

assessment of household water prices and indicative CAPEX–OPEX conditions; and (4) synthesis of scale-appropriate drinking water supply strategies. Cross-case consistency and data triangulation are used to strengthen analytical interpretation.

## 2.8 Comparative analytical strategy

The analysis applies descriptive comparison and cross-case assessment to identify recurring structural patterns across the selected islands. Emphasis is placed on consistency between population scale, freshwater availability, household water access conditions, and the suitability of different drinking water supply strategies. The study focuses on comparative interpretation and policy relevance rather than formal statistical inference.

## 3. RESULTS AND DISCUSSION

### 3.1 Results

#### 3.1.1 Characteristics of the 15 case study islands

A total of 15 inhabited islands were analyzed across Indonesia’s five major island regions. A detailed summary of island characteristics, estimated water demand, dominant water sources, water prices, and freshwater availability is presented in Table 10.

While most cases fall within the micro-island category ( $\leq 200$  inhabitants), two islands (Owi and Ur) represent upper-bound small island conditions to enable scale comparison.

These islands generally lack permanent freshwater sources and rely primarily on rainwater harvesting or purchased water. Water prices on small islands range from Rp 300 to Rp 600 per liter, compared to mainland PDAM tariffs of approximately Rp 3–6 per liter, resulting in households on small islands paying 50–200 times higher prices. For low-income households, water expenditures can account for 10–20% of total monthly household spending.

#### 3.1.2 Observed water consumption (2019–2023)

The observed consumption ranges and scale characteristics across island categories are summarized in Table 11.

Across 132 validated households (2019–2023): (1) Micro islands ( $\leq 200$  inhabitants): 45–65 L/cap/day; (2) Upper-bound micro ( $\sim 180$ –200 inhabitants): 60–70 L/cap/day; (3) No island exceeded 80 L/cap/day during the dry season.

All micro-island cases remain below 15 m<sup>3</sup>/day.

Institutional water demand across micro islands was minimal. Observed elementary schools (20–60 students) and small prayer facilities contributed an estimated additional 1–2 m<sup>3</sup>/day, representing less than 8–10% of total island demand. This increment does not materially alter the scale classification of micro islands ( $< 15$  m<sup>3</sup>/day).

#### 3.1.3 Seasonal variation (Observed pattern)

As summarized in Table 12, seasonal variations affect water consumption patterns, purchased water dependency, refill frequency, and water prices across all study islands. No island achieved year-round freshwater sufficiency without supplementation.

**Table 10.** Characteristics of case study islands and water access conditions

Island	Province	Population	Dominant Source	Estimated Demand (m <sup>3</sup> /day)*	Water Price (Rp/L)	Price Ratio vs. Mainland	Responsible Water Utility (PDAM)	Permanent Freshwater
Tailana	Aceh	200–250	Rainwater	10–14	300–500	50–120×	PDAM Aceh Singkil Regency	No
Salah Namu	North Sumatra	100–300	Transported	5–12	400–600	80–150×	PDAM Langkat Regency	No
Berhala Kecil	Jambi	80–250	Rainwater	4–10	300–500	50–120×	PDAM East Tanjung Jabung Regency	No
Pamujan Kecil	Banten	90–180	Bottled	4–8	400–600	80–150×	PDAM Serang Regency	No
Bidadari	East Java	80–200	Brackish wells	4–12	300–500	50–120×	PDAM Sumenep Regency	No
Gili Raja Kecil	East Java	90–190	Rainwater	5–13	300–500	50–120×	PDAM Sumenep Regency	No
Nunukan Island	North Kalimantan	80–170	Purchased	4–10	400–600	80–150×	PDAM Nunukan Regency	No
Maratua Kecil	East Kalimantan	70–150	Rainwater	3–8	300–500	50–120×	PDAM Berau Regency	No
Pulau Manti	South Kalimantan	60–140	Transported	3–7	400–600	80–150×	PDAM Kotabaru Regency	No
Langkai	South Sulawesi	90–150	Rainwater	5–8	300–500	50–120×	PDAM Makassar City	No
Kulambing	South Sulawesi	80–160	Brackish wells	4–10	300–500	50–120×	PDAM Pangkep Regency	No
Gangga	North Sulawesi	80–160	Purchased	4–9	400–600	80–150×	PDAM North Minahasa Regency	No
Owi	Papua	300–450	Rainwater	24–40	300–500	50–120×	PDAM Biak Numfor	No
Ur	Maluku	745–783	Transported	45–62	400–600	80–150×	PDAM Kota Tual	No
Numfor Kecil	Papua	100–180	Shallow wells	5–13	300–500	50–120×	PDAM Biak Numfor Regency	No

**Table 11.** Observed consumption and scale characteristics

Category	Population Range	Observed L/Cap/Day	Absolute Demand Range	Institutional Share	On-Grid System
Micro	≤ 200	45–70	2.5–14 m <sup>3</sup> /day	< 8%	None
Small	200–1,000	60–80	12–80 m <sup>3</sup> /day	< 10%	None
Medium	1,000–10,000	80–100	80–1,000 m <sup>3</sup> /day	Moderate	Limited
Large	> 10,000	100–120	> 1,000 m <sup>3</sup> /day	Significant	Present

**Table 12.** Seasonal dynamics of water access

Indicator	Wet Season	Dry Season
Per capita consumption	+ 10–15%	Baseline
Purchased water share	20–40%	60–70%
Refill frequency	Moderate	+ 30–50%
Price variation	Baseline	+ 10–15%

### 3.1.4 Verified water prices (2019–2024)

As shown in Table 13, water prices on micro islands remain substantially higher than mainland PDAM tariffs. The 50–200× ratio is consistently observed across all micro-island cases.

**Table 13.** Water price comparison

Indicator	Micro Islands	Mainland PDAM
Retail price (Rp/L)	300–600	3–6
Equivalent (Rp/m <sup>3</sup> )	300,000–600,000	3,000–6,000
Expenditure share	10–20% income	< 3% income

### 3.1.5 Comparative CAPEX–OPEX across drinking water supply strategies

Table 14 summarizes the indicative capital and operating cost ranges associated with different drinking water supply strategies across island population scales.

**Table 14.** Indicative capital and operating cost ranges

Strategy	Scale	CAPEX (Rp/Person)	OPEX (Rp/m <sup>3</sup> )
Micro RO	≤ 200	8–15 million	10,000–20,000
RWH + UV	≤ 200	3–7 million	< 5,000
Hybrid RWH–RO	200–1,000	6–10 million	8,000–15,000
Off-grid SPAM	1,000–10,000	4–8 million	5,000–10,000
On-grid	> 10,000	2–5 million	< 5,000

## 3.2 Discussion

The analysis results indicate that water scarcity on small

islands is structural in nature and cannot be resolved through on-grid approaches or population relocation. The most rational solution is island-scale off-grid systems, such as micro-scale reverse osmosis (RO) and integrated rainwater harvesting, managed at the community level with support from state policies.

### 3.2.1 Structural constraint and demand magnitude

Empirical findings show that all micro-island cases ( $\leq 200$  inhabitants) exhibit absolute domestic water demand below  $15 \text{ m}^3/\text{day}$ , absence of permanent freshwater sources, and dependence on rainwater, transported water, or saline groundwater. These three variables—demand magnitude, raw water availability, and supply dependence—form a consistent structural pattern across geographically dispersed islands.

The critical feature is not merely water scarcity, but the interaction between hydrogeological limitation and extremely small demand volume. Even where rainfall is present, limited catchment area and shallow aquifers prevent stable freshwater accumulation. Thus, water insecurity is not seasonal variability alone, but structural hydrological constraint combined with minimal demand aggregation.

### 3.2.2 Scale threshold and system feasibility

Observed demand volumes ( $< 15 \text{ m}^3/\text{day}$  for micro islands) are substantially below the production scales typically associated with centralized utility systems. Centralized systems rely on: (1) Continuous raw water abstraction; (2) Aggregated demand; (3) Network-based distribution; (4) Capital amortization over large customer bases.

Where production volume remains permanently small, fixed infrastructure costs are distributed over extremely low output. Under such conditions, centralized expansion does not generate efficiency gains.

The empirical evidence therefore indicates that micro islands operate below the functional scale at which conventional utility models become viable. This mismatch is structural and persistent. This finding is consistent with previous studies on small-island water systems, which demonstrate that low population density, geographic isolation, limited freshwater availability, and high infrastructure costs constrain the economic viability of centralized water supply networks. Consequently, decentralized approaches such as rainwater harvesting, small-scale desalination, and community-managed systems are frequently identified as the most appropriate solutions for remote island settlements [18].

Similar observations have been reported in other island settings, where low demand volumes, geographic isolation, and limited resource availability constrain the viability of centralized water supply systems. In such contexts, decentralized and community-scale systems are frequently identified as more appropriate service models due to their flexibility and lower infrastructure requirements [25-27].

### 3.2.3 Cost structure and household burden

Water price data reveal a consistent ratio of  $50\text{--}200\times$  relative to mainland tariffs, with household expenditures reaching  $10\text{--}20\%$  of monthly income. This pattern reflects the economic consequence of small-scale supply fragmentation.

Indicative CAPEX–OPEX analysis shows that while per-capita capital costs of micro systems are higher than large-scale systems, total absolute investment remains modest due to small population size. Moreover, operational costs of modular systems are substantially lower than prevailing

purchased-water prices.

This implies that replacing informal purchased-water dependence with structured off-grid systems would reduce household economic burden despite higher per-capita capital cost.

### 3.2.4 Governance alignment with scale conditions

Although all islands fall under administrative responsibility of local utilities, none of the micro-island cases is operated through centralized on-grid systems. Operational arrangements are community-based, semi-formal, or dependent on external transport.

This divergence between administrative mandate and operational reality reflects scale misalignment rather than institutional absence. Expanding centralized mandate without adjusting system architecture would not alter the underlying scale constraint.

### 3.2.5 Technology emergence as structural response

Across cases, three system types appear consistently: (1) Micro reverse osmosis units in islands without viable freshwater; (2) Rainwater harvesting with basic treatment where rainfall reliability permits; (3) Hybrid configurations in upper-bound population cases.

Technology selection aligns directly with demand magnitude and raw water conditions. No case demonstrates sustainable centralized on-grid operation under micro-island conditions.

The empirical pattern therefore indicates that system choice is constrained by physical and demographic parameters rather than by policy preference.

Recent advances in modular desalination technologies, renewable-energy integration, and distributed rainwater harvesting systems further strengthen the feasibility of decentralized water supply approaches for remote island settlements. These technologies are increasingly recognized as practical alternatives for achieving water security under severe physical and demographic constraints.

## 4. CONCLUSION

Across all surveyed micro islands ( $\leq 200$  inhabitants), three structural characteristics consistently recur: limited land area with narrow hydrological catchment, high vulnerability to seawater intrusion, and extremely small aggregated domestic water demand ( $< 15 \text{ m}^3/\text{day}$ ). Even where rainfall is adequate, storage limitations and shallow or saline aquifers prevent the establishment of permanent freshwater sources. Water scarcity under these conditions is therefore structural and spatial in nature rather than a temporary seasonal imbalance.

From a demand perspective, populations at or below 200 inhabitants generate volumes that are inherently small in absolute terms. This minimal aggregation fundamentally shapes system feasibility. The operational environment of micro islands is defined by the simultaneous presence of hydrogeological fragility and permanently low demand magnitude.

Centralized utility systems, by contrast, depend on continuous raw water abstraction, demand aggregation, network economies, and capital amortization across large user bases. Empirical evidence shows that none of the surveyed micro islands operates under such conditions. Production volumes remain permanently low, and raw water sources are

unreliable or saline. Under these circumstances, fixed infrastructure costs cannot be efficiently distributed, and unit production costs increase as output declines. Expanding centralized networks into micro-island environments does not alter these scale fundamentals.

Observed system patterns indicate that only three configurations consistently align with micro- and small-island conditions: micro reverse osmosis units where seawater or brackish sources dominate, rainwater harvesting with basic disinfection where rainfall reliability permits, and hybrid RWH–RO systems for upper-bound micro populations. These systems match low production volumes, avoid extensive distribution networks, and allow modular capital deployment with localized operation. No empirical case supports sustainable centralized on-grid provision under micro-island conditions.

Taken together, the findings demonstrate that drinking water insecurity on very small inhabited islands is the product of interacting structural variables: hydrogeological limitation, extremely small demand volume, and absence of scalable aggregation. Micro islands operate below the effective scale required for centralized utility systems. Under these conditions, modular off-grid systems constitute the only

configurations consistently compatible with observed demand levels and raw water realities. Water provision in archipelagic settings must therefore be structured around scale-differentiated system design rather than uniform infrastructure expansion.

Although not explicitly framed as interrogative statements in the introduction, this study is guided by three underlying research questions derived from the structural, scale, and policy gaps identified in earlier sections. The empirical synthesis directly addresses each of these questions, as summarized in Table 15.

The answers to these research questions converge on a single structural insight: scale is the decisive variable linking physical constraint, economic feasibility, institutional performance, and technology selection. In very small island contexts, infrastructure design cannot be detached from demographic magnitude and hydrogeological limitations. Accordingly, drinking water insecurity in archipelagic states should not be interpreted as a failure of utility expansion, but as a consequence of applying uniform system logic to fundamentally heterogeneous spatial scales. Sustainable provision requires system architectures that are explicitly aligned with island-scale thresholds.

**Table 15.** Research questions, key findings, and structural implications

Research Question	Analytical Focus	Key Empirical Findings	Structural Implication
<b>RQ-1:</b> What structural characteristics constrain freshwater availability on very small islands?	Hydrogeological–demographic	Micro islands ( $\leq 200$ inhabitants) exhibit limited catchment areas, saline or brackish groundwater, absence of permanent freshwater, and absolute demand $< 15 \text{ m}^3/\text{day}$ .	Water scarcity is inherent to physical and demographic scale, not a temporary supply failure.
<b>RQ-2:</b> Why are centralized water utilities–based systems unviable?	Institutional–scale	Observed demand volumes remain far below typical centralized production thresholds; no island in the sample operates an on-grid system; high unit costs persist under low output.	Service failure reflects structural scale incompatibility rather than institutional weakness.
<b>RQ-3:</b> What scale-appropriate solutions ensure sustainable access?	System design–policy	Micro RO, rainwater harvesting with basic treatment, and hybrid systems consistently align with demand magnitude and raw water constraints.	Island-category-based system differentiation is required for sustainable provision.

## 5. RECOMMENDATION

The implications presented below are derived from RQ-1 (structural constraints), RQ-2 (scale incompatibility), and RQ-3 (scale-appropriate configurations) and directly reflect the structural relationships identified in Section 4.

Empirical findings indicate that drinking water insecurity on micro islands ( $\leq 200$  inhabitants) is structurally determined by the interaction of three key variables: limited hydrogeological capacity, extremely low absolute demand ( $< 15\text{--}20 \text{ m}^3/\text{day}$ ), and the absence of scalable aggregation. Under these conditions, centralized utility-based systems consistently operate below their effective production threshold.

Accordingly, infrastructure planning must shift from uniform expansion models toward scale-differentiated system design. First, island categories should be formally defined based on population size and demand magnitude, as micro islands require system typologies fundamentally distinct from mainland utility frameworks. Second, governance structures must be aligned with operational scale. While utilities may retain regulatory and technical oversight roles, operational management in micro-island contexts should be adapted to localized, low-volume configurations. Third, capital allocation

should prioritize modular off-grid systems. Although per-capita capital costs tend to be higher at smaller scales, total absolute investment remains limited, and operational costs are significantly lower than prevailing informal water prices. Finally, technology deployment should be guided by demand thresholds rather than uniform policy templates: (1)  $\leq 200$  inhabitants: modular micro-systems (e.g., RO or RWH-based); (2) 200–1,000 inhabitants: hybrid localized systems; (3)  $\geq 10,000$  inhabitants: centralized on-grid systems.

In archipelagic contexts, drinking water provision must therefore be structured around demographic and geographic scale as primary design variables. Scale-differentiated planning is not merely a policy preference, but a structural necessity for achieving sustainable water access [28-31].

## ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of the National Research and Innovation Agency (BRIN), Indonesia, for facilitating this research through institutional research support and technical collaboration. The authors also thank regional stakeholders, local communities, and field

respondents across the surveyed island locations for their assistance during field verification activities conducted between 2019 and 2023. Appreciation is further extended to reviewers and editors for their constructive comments, which substantially improved the quality and clarity of this manuscript.

## AUTHOR CONTRIBUTIONS

The study was primarily conceptualized, designed, and led by Nicco Plamonia, who was responsible for developing the research framework, comparative analytical approach, interpretation of findings, and preparation of the original manuscript draft. Nicco Plamonia also coordinated the overall research process, integrated the analytical sections, and served as the corresponding author. Rizki Arizal Purnama and Wahyu Purwanta contributed to methodological development, analytical refinement, and manuscript review. Yeni Novitasari, Elshedevika Rosya, Heru Mulyono, and Rizki Firmansyah contributed to data interpretation, policy analysis, and technical discussion. Dwi Budiyanto Trisnoharjono, Ahmad Nuridha, Indri Mardiyana, Suwarti Wati, Agus Setiawan, and Susilo Raharjo supported technical validation, engineering interpretation, and review of the manuscript. Revina Devitani Putri assisted with literature compilation, data organization, and manuscript preparation. All authors reviewed and approved the final version of the manuscript.

## DATA AVAILABILITY STATEMENT

The data supporting the findings of this study were derived primarily from publicly available secondary sources, including datasets and reports from Badan Informasi Geospasial (BIG), Badan Pusat Statistik (BPS), BRIN technical reports, regional government documents, and previously published literature. Limited field verification data collected between 2019 and 2023 were used to corroborate secondary findings. Due to the combination of institutional reports, observational field notes, and partially unpublished verification materials, some supporting datasets are available from the corresponding author upon reasonable request.

## REFERENCES

- [1] Badan Informasi Geospasial. (2024). Pulau Indonesia bertambah jadi 17.380, mengapa angkanya berubah setiap tahun? Badan Informasi Geospasial. [https://www.big.go.id/uploads/downloads/Dokumen/Rilis\\_Jumlah\\_Pulau.pdf](https://www.big.go.id/uploads/downloads/Dokumen/Rilis_Jumlah_Pulau.pdf).
- [2] Badan Informasi Geospasial. (2021). *Gazeter Republik Indonesia*. Jakarta, Indonesia, Badan Informasi Geospasial. [https://sinar.big.go.id/assets/document/gazeter/gazeter\\_1643095453.pdf](https://sinar.big.go.id/assets/document/gazeter/gazeter_1643095453.pdf).
- [3] Connell, J., Lowitt, K., Ville, A.S., Hickey, G.M. (2020). *Food Security in Small Island States*. Springer. <https://doi.org/10.1007/978-981-13-8256-7>
- [4] Coulon, C., White, J.T., Pryet, A., Gatel, L., Lemieux, J.-M. (2024). An ensemble-based approach for pumping optimization in an island aquifer considering parameter, observation and climate uncertainty. *Hydrology and Earth System Sciences*, 28(1): 303-319. <https://doi.org/10.5194/hess-28-303-2024>
- [5] Mohsen, M.S. (2007). Water strategies and potential of desalination in Jordan. *Desalination*, 203(1-3): 27-46. <https://doi.org/10.1016/j.desal.2006.03.524>
- [6] Still, D.A. (1991). Small scale desalination in South Africa with particular reference to solar distillation. OpenUCY, 1.1-9.1. <http://hdl.handle.net/11427/12585>.
- [7] Patton, C., Sawicki, D., Clark, J. (2015). *Basic Methods of Policy Analysis and Planning*. Routledge. <https://doi.org/10.4324/9781315664736>
- [8] Dale, A., Arber, S., Procter, M. (2025). *Doing Secondary Analysis*. London: Routledge.
- [9] Levy, J.S. (2008). Case studies: Types, designs, and logics of inference. *Conflict Management and Peace Science*, 25(1): 1-18. <https://doi.org/10.1080/07388940701860318>
- [10] Beach, D., Pedersen, R.B. (2016). *Causal Case Study Methods: Foundations and Guidelines for Comparing, Matching, and Tracing*. Ann Arbor, University of Michigan Press. <https://doi.org/10.3998/mpub.6576809>
- [11] Borman, K.M., Clarke, C., Cotner, B., Lee, R. (2012). Cross-case analysis. In *Handbook of Complementary Methods in Education Research*, pp. 123-139. <https://www.routledge.com/9780203874769>.
- [12] Hehanussa, P.E. (2002). Ecohydrology and Tectogenesis of small islands in Indonesia. In *Hydrology and Water Management in the Humid Tropics*.
- [13] Holding, S., Allen, D.M., Foster, S., Hsieh, A., Larocque, I., Klassen, J., Van Pelt, S.C. (2016). Groundwater vulnerability on small islands. *Nature Climate Change*, 6(12): 1100-1103. <https://doi.org/10.1038/nclimate3128>
- [14] Kumar, P., Avtar, R., Dasgupta, R., Johnson, B.A. (2020). Socio-hydrology: A key approach for adaptation to water scarcity and achieving human well-being in large riverine islands. *Progress in Disaster Science*, 8: 100134. <https://doi.org/10.1016/j.pdisas.2020.100134>
- [15] Terry, J.P., Falkland, A.C. (2009). Responses of atoll freshwater lenses to storm-surge overwash in the Northern Cook Islands. *Hydrogeology Journal*, 18(3): 749-759. <https://doi.org/10.1007/s10040-009-0544-x>
- [16] Bailey, R.T., Jenson, J.W., Olsen, A.E. (2010). Estimating the ground water resources of atoll islands. *Water*, 2(1): 1-27. <https://doi.org/10.3390/w2010001>
- [17] White, I., Falkland, T. (2009). Management of freshwater lenses on small Pacific islands. *Hydrogeology Journal*, 18(1): 227-246. <https://doi.org/10.1007/s10040-009-0525-0>
- [18] Griffin, R.C. (2016). *Water Resource Economics: The Analysis of Scarcity, Policies, and Projects*. MIT Press. <https://mitpress.mit.edu/9780262034043/water-resource-economics/>.
- [19] O'Connell, E. (2017). Towards adaptation of water resource systems to climatic and socio-economic change. *Water Resources Management*, 31(10): 2965-2984. <https://doi.org/10.1007/s11269-017-1734-2>
- [20] Birawida, A.B., Ibrahim, E., Mallongi, A., Rasyidi, A.A.A., Thamrin, Y., Gunawan, N.A. (2021). Clean water supply vulnerability model for improving the quality of public health (environmental health perspective): A case in Spermonde islands, Makassar Indonesia. *Gaceta Sanitaria*, 35(S2): S601-S603. <https://doi.org/10.1016/j.gaceta.2021.10.095>
- [21] Ghaffour, N., Missimer, T.M., Amy, G.L. (2013).

- Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability. *Desalination*, 309: 197-207. <https://doi.org/10.1016/j.desal.2012.10.015>
- [22] Elliott, M., MacDonald, M.C., Chan, T., Kearton, A., Shields, K.F., Bartram, J.K., Hadwen, W.L. (2017). Multiple household water sources and their use in remote communities with evidence from Pacific Island countries. *Water Resources Research*, 53(11): 9106-9117. <https://doi.org/10.1002/2017WR021047>
- [23] White, I., Falkland, T. (2015). Integrated management of urban water supply and water quality in developing Pacific Island countries. In *Global Issues in Water Policy*, Springer, pp. 489-526. <https://researchportalplus.anu.edu.au/en/publications/integrated-management-of-urban-water-supply-and-water-quality-in->
- [24] IPCC. (2014). Small islands. in *Climate Change 2014: Impacts, Adaptation, and Vulnerability*, pp. 1613-1654. <https://doi.org/10.1017/CBO9781107415386.009>
- [25] Olufisayo, O.E., Olanrewaju, O. (2024). A review of renewable energy powered seawater desalination treatment process for zero waste. *Water*, 16(19): 2804. <https://doi.org/10.3390/w16192804>
- [26] Mycoo, M.A. (2017). Beyond 1.5 °C: Vulnerabilities and adaptation strategies for Caribbean Small Island Developing States. *Regional Environmental Change*, 18(8): 2341-2353. <https://doi.org/10.1007/s10113-017-1248-8>
- [27] Campisano, A., Butler, D., Ward, S., Burns, M.J., Friedler, E., DeBusk, K., Fisher-Jeffes, L.N., Ghisi, E., Rahman, A., Furumai, H., Han, M. (2017). Urban rainwater harvesting systems: Research, implementation and future perspectives. *Water Research*, 115: 195-209. <https://doi.org/10.1016/j.watres.2017.02.056>
- [28] Fritzmann, C., Löwenberg, J., Wintgens, T., Melin, T. (2007). State-of-the-art of reverse osmosis desalination. *Desalination*, 216(1-3): 1-76. <https://doi.org/10.1016/j.desal.2006.12.009>
- [29] Elimelech, M., Phillip, W.A. (2011). The future of seawater desalination: Energy, technology, and the environment. *Science*, 333(6043): 712-717. <https://doi.org/10.1126/science.1200488>
- [30] Karagiannis, I.C., Soldatos, P.G. (2008). Water desalination cost literature: Review and assessment. *Desalination*, 223(1-3): 448-456. <https://doi.org/10.1016/j.desal.2007.02.071>
- [31] Shannon, M.A., Bohn, P.W., Elimelech, M., Georgiadis, J.G., Mariñas, B.J., Mayes, A.M. (2008). Science and technology for water purification in the coming decades. *Nature*, 452(7185): 301-310. <https://doi.org/10.1038/nature06599>