Hydro-Oceanographic Controls on Water Quality and Artificial Reef Sustainability in a Data-Limited Tropical Coastal System

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ABSTRACT

Artificial Reefs (ARs) are utilized as ecological engineering tools to rehabilitate degraded coral reefs; however, their long-term performance strongly depends on local hydro-oceanographic conditions. This study presents a practical field and data-processing protocol for seawater quality monitoring around cube-shaped ARs deployed in 2017 at Damas Beach, Prigi Bay, East Java, revisited in August 2024 during the southeast monsoon. Six stations surrounding the ARs were surveyed for in situ temperature, salinity, Dissolved Oxygen (DO), pH, current speed, turbidity, and q depth (water clarity), while nitrate and phosphate concentrations were analyzed ex-situ. The Secchi Depth (*SD*) ranged from 1.3–4.5 m and turbidity from 19.00–35.78 NTU, indicating highly turbid conditions. The currents were very weak (0–0.1 m/s, mean 0.07 m/s), favoring local sediment deposition around the structures. In contrast, the temperature (24.69–25.77 °C), influenced by monsoon-driven upwelling, salinity (34.00–34.52 ppt), DO (6.68–6.80 mg/L), and pH (7.3–8.0) were within the range suitable for coral reef organisms. Nutrient concentrations were enriched, with nitrate concentrations of 1.746–1.842 mg/L and phosphate concentrations of 0.0947–0.3307 mg/L, consistent with terrestrial inputs from the watershed. Overall, the Damas case demonstrates how the proposed minimum parameter set and workflow can generate a replicable hydro-oceanographic baseline to support routine monitoring and adaptive management of AR sites in data-limited tropical coastal systems.

Keywords-artificial reefs; hydro-oceanography; nutrient enrichment; turbidity and sedimentation; water quality

I. INTRODUCTION

ARs are structures intentionally placed on the seafloor for ecological and socio-economic purposes. They can be built from natural or artificial materials in various forms, such as reef balls, concrete pipes, cubes, or shipwrecks, generally using sand or cement as the main components. ARs are designed to function as new habitats that support marine life, including serving as substrates for coral larvae attachment [1]. In Indonesia, early AR development mainly aimed to enhance fish catch. Since 1988, various AR designs and Fish Aggregating Devices (FADs) have been deployed to attract pelagic fish, including concrete blocks measuring 1.2 × 0.7 × 0.7 m and even decommissioned vehicles [1]. More recently, greater attention has been given to ARs design, configuration, and base materials, as these factors influence their effectiveness in attracting biota, stabilizing currents, and providing spawning and nursery grounds for the fish [2].

The long-term success of AR implementation is strongly controlled by local water quality. Physical factors, such as temperature, currents, clarity, and sediment dynamics [2], together with chemical factors, such as salinity, pH, DO, nitrate and phosphate concentrations [3, 4], determine whether ARs can function as stable and productive habitats. At Damas Beach, Trenggalek, several studies have highlighted the role of oceanographic parameters in coral reef growth and AR-assisted rehabilitation. External stressors, including El Niño-induced coral bleaching, sedimentation from terrestrial sources, and destructive fishing practices (nets, potassium, and explosives), have accelerated the degradation of natural coral reefs [1, 2]. Cube-shaped ARs having been deployed at Damas Beach since 2017 remain mostly intact, but some structures are covered by sediment or fishing nets, suggesting that their functionality is directly affected by the surrounding water quality.

Existing studies on Damas waters have mainly described the ecology of cube-shaped ARs and nearby natural coral reefs, as well as selected oceanographic drivers. Previous research includes assessments of cube AR ecology and associated biota [1], physical oceanography around ARs [2], the relationship between chemical water quality and natural coral reefs [3, 4], dynamics of Total Suspended Solids (TSS) around coral reef areas [5], and biofouling colonization on cubic ARs [6]. While these works provide important baseline information, they were conducted shortly after AR deployment or focused on specific components of the hydro-oceanographic system without integrating a full suite of water quality parameters to evaluate AR conditions several years after deployment. This gap limits cross-study comparability, reduces reproducibility, and constrains the ability of managers to apply consistent monitoring under data- and resource-limited settings.

Therefore, this study presents a practical field and data-processing protocol for hydro-oceanographic and seawater-quality monitoring around cube-shaped Ars at Damas Beach (field campaign in August 202 during southeast monsoon). The protocol involves a minimum, replicable parameter set covering key physical variables (depth, temperature, water clarity/*SD*, current velocity, and turbidity) and chemical parameters (salinity, pH, DO, nitrate, and phosphate ions concentrations). The Damas dataset is provided as an implementation example to show how the workflow can generate a standardized baseline for routine monitoring and adaptive management of AR sites in Prigi Bay and other data-limited tropical coastal systems. This baseline supports an evidence-based evaluation of conditions that may enable or constrain long-term AR functionality and coral recruitment.

II. METHODS

A. *Study Area*

This study was conducted in the coastal waters of Damas Beach, Karanggandu Village, Watulimo District, Trenggalek Regency, East Java (Figure1). Data collection was carried out in August 2024, representing the southeast monsoon season, at six sampling stations (Table I). The latter were selected to cover the main spatial gradient in the semi-enclosed Damas Bay, combining clustered points around the AR sites with additional nearshore/exposed points to represent variability in currents and turbidity under practical field constraints. The bay-like morphology provides partial protection from large waves, while coastal circulation remains influenced by monsoon- and tide-driven currents. Previous measurements in Damas reported current speeds of approximately 0.1–0.4 m/s [2]. The seabed substrate is dominated by mud and fine sand, contributing to relatively high-water turbidity, particularly during the rainy season [5].

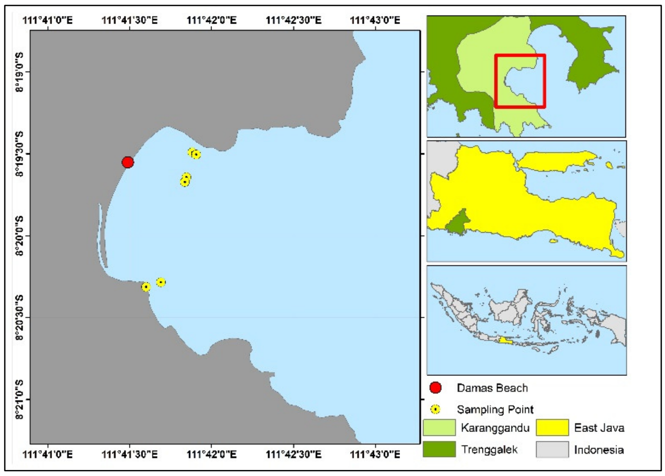

Fig. 1. Study area and location of the sampling stations at Damas Beach, Trenggalek, East Java, Indonesia (WGS84).

TABLE I. COORDINATES OF THE SIX SAMPLING POINTS

Station	Latitude	Longitude
1	-8.324836537	111.6980445
2	-8.32506193	111.6984535
3	-8.327379077	111.6974497
4	-8.327858735	111.697278
5	-8.338065162	111.6948441
6	-8.338547155	111.6933375

B. *Data Collection*

In situ measurements were conducted at the six sampling stations (water depths 5-8 m) during low tide in the morning (08:00–11:00 local time). The current speed was measured using a Flowatch current meter (60 s per replicate), following the operational workflow and field setup shown in Figure 2. Water transparency was measured as *SD* using a Secchi disk, following the workflow and field illustration illustrated in Figure 3 [7]. For nutrient analysis, nitrate and phosphate were collected as composite (pooled) samples for station pairs (1–2), (3–4), and (5–6) due to resource constraints and to prioritize the main transect across the AR area. The sampling and field handling are displayed in Figure 4. The samples were stored in polyethylene bottles and analyzed in the laboratory. Temperature, salinity, and DO were recorded using an AAQ Rinko 1183, following the field procedures portrayed in Figure 5. The pH was measured using a portable pH meter (Table II). Several measurements were taken on the water surface at ~0.5 m below the surface and repeated three times at each station.

TABLE II. INSTRUMENTS USED FOR WATER QUALITY DATA COLLECTION AND MEASURED PARAMETERS

No.	Instrument	Parameter
1	Current meter (Flowatch)	Water current speed
2	Secchi disk	*SD*
3	Polyethylene bottle	Nitrate and phosphate
4	AAQ Rinko 1183	Temperature, salinity, DO

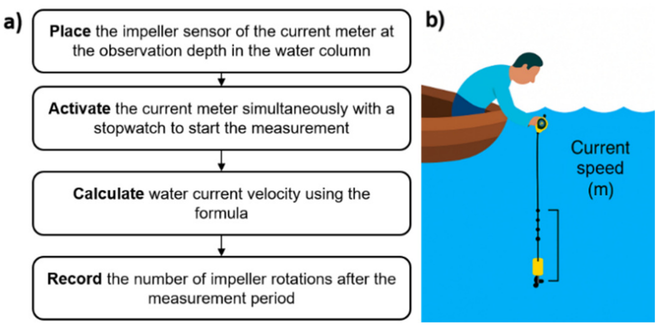

Fig. 2. Current-speed measurement using a Flowatch current meter: (a) operational flowchart and (b) field illustration.

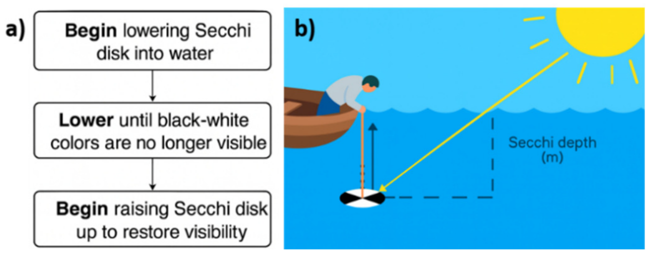

Fig. 3. Water transparency measurement using a Secchi disk: (a) operational flowchart and (b) field illustration.

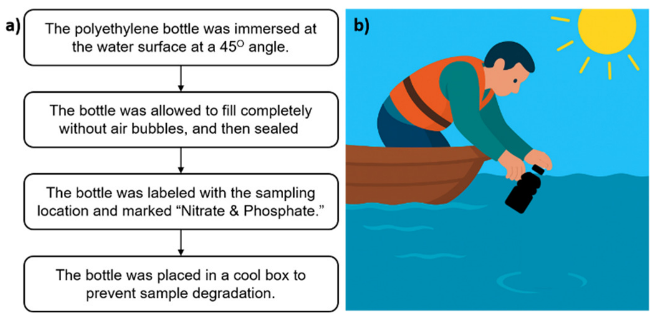

Fig. 4. Nitrate and phosphate measurements using a polyethylene bottle: a) flowchart and b) field illustration.

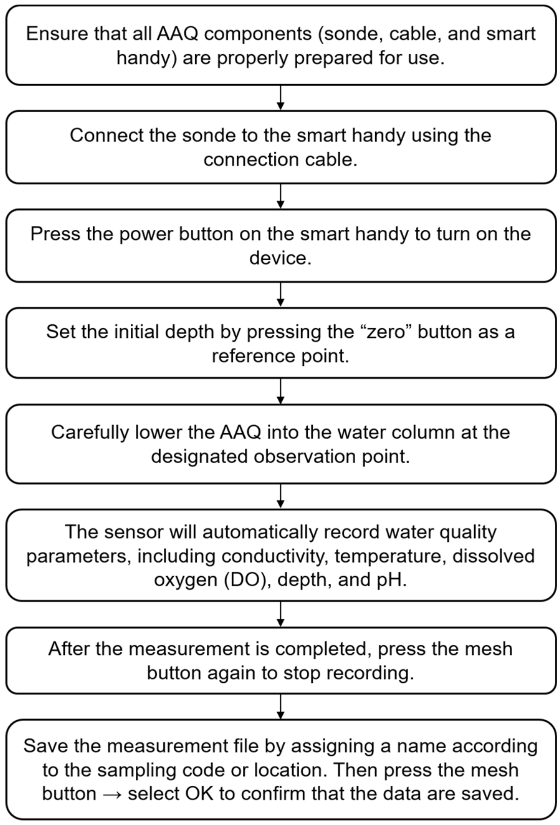

Fig. 5. Data collection flowchart using the AAQ Rinko device.

C. Data Processing

In situ data from the six sampling stations were processed by calculating the mean of three measurements for each parameter (temperature, salinity, DO, current speed, pH, and *SD*). Extreme values were rechecked against field notes and instrument stability to avoid biasing the results. Nitrate and phosphate concentrations were reported in mg/L and were analyzed by the Environmental Laboratory of Perum Jasa Tirta I under an ISO/IEC 17025:2017 quality system and the results were verified through routine laboratory QA/QC consistent with the accredited methods stated in the laboratory test certificate (e.g., relevant SNI procedures).

The Secchi disk depth represents water clarity. The measurements followed established Secchi-disk practice, as described in the HELCOM Guidelines for measuring *SD*. The former were performed by lowering the disk on the shaded side of the boat until it disappeared from view (d_1), and then raising it slowly until it reappeared (d_2), with the line kept as vertical as possible. *SD* was calculated as the arithmetic mean of the two depths:

$$SD = \frac{d_1+d_2}{2} \quad (1)$$

The current speed was measured using a Flowatch current meter. The number of impeller rotations (n) recorded over the measurement period (t) was estimated with (2) and used to compute current speed following SNI 3408:2015 in (3) [8]:

$$N = \frac{n}{t} \quad (2)$$

$$v = a \cdot N + b \quad (3)$$

where v is the current speed (m/s), a and b are calibration constants (state source), and N is the impeller rotational rate (rev/s or rpm).

D. Design Limitations

This study was based on a single field campaign (August 2024, southeast monsoon) at six stations around the ARs site. Nutrients were analyzed as three composite station pairs due to resource constraints. Therefore, the dataset is presented as a baseline implementation example of the proposed monitoring protocol, rather than a full-year characterization of the conditions at Damas Beach.

III. RESULTS AND DISCUSSION

The hydro-oceanographic parameters, consisting of physical parameters (*SD*, temperature, current velocity, and turbidity) and chemical parameters (salinity, dissolved oxygen/DO, and pH), measured in situ and ex situ, are presented in Table III.

A. Temperature

The water temperature at Damas Beach ranged from 24.69°C to 25.77°C, with a mean temperature of 25.19 ± 0.46°C, indicating relatively cool and stable conditions that support marine life (Table III). Such temperatures are characteristic of the southeast monsoon along the southern coasts of Java, Bali, and Nusa Tenggara, where wind-driven upwelling brings cooler subsurface waters to the surface [9]. This seasonal cooling reduces the risk of thermal stress and bleaching for corals and reef-associated organisms and is generally favorable for growth and metabolism. For the ARs at Damas, the observed temperature range suggests that thermal conditions during the August 2024 survey were suitable for AR-based coral rehabilitation; however, longer-term monitoring across different monsoon phases is still required to fully evaluate thermal suitability.

B. Salinity

The salinity at Damas Beach ranged from 34.00 to 34.52 ppt, with a mean salinity of 34.36 ± 0.17 ppt (Table III), remaining within the typical seawater range of 33–35 ppt, thus supporting normal osmotic regulation in marine organisms. Although abrupt salinity fluctuations can induce physiological stress and impair the growth and survival of fish and invertebrates [9], the narrow range observed during the August 2024 southeast monsoon survey indicates that salinity did not pose a major constraint on the AR community. Under these stable conditions, other factors, such as turbidity, sedimentation, and nutrient enrichment, are likely to play a more dominant role in controlling the long-term performance of the cube-shaped ARs at Damas Beach.

C. Dissolved Oxygen

The DO concentrations at Damas Beach ranged from 6.68 to 6.80 mg/L, with a mean of 6.75 ± 0.05 mg/L (Table III), clearly exceeding the commonly used minimum threshold of 5 mg/L required to sustain marine life. These values indicate well-oxygenated conditions, likely maintained by adequate water mixing and photosynthetic activity, and suggest limited organic loading in the study area [10]. For the cube-shaped ARs, such DO levels are sufficient to support the aerobic metabolism of corals, fish, and associated biofouling communities and to minimize the risk of hypoxia within sheltered cavities. Therefore, DO was not considered a limiting factor for AR performance at Damas Beach compared to more critical constraints such as turbidity, sedimentation, and nutrient enrichment.

D. pH

The recorded pH values at Damas Beach ranged from 7.3 to 8.0, with a mean of 7.60 ± 0.24 (Table III), which falls within the typical range of 7.0–8.5 commonly reported for Indonesian tropical waters [11]. Within this interval, seawater carbonate chemistry generally remains suitable for coral calcification and shell formation in other calcifying organisms. So, pH is not expected to substantially limit coral growth or the structural integrity of calcareous biota colonizing the cube-shaped ARs. Compared with more critical constraints, such as high turbidity, sedimentation, and nutrient enrichment, pH can therefore be considered a secondary factor for AR performance at Damas Beach.

E. Turbidity

The turbidity values at Damas Beach ranged from 19.00 to 35.78 NTU, with a mean of 24.84 ± 5.40 NTU, far exceeding the proposed threshold of <5 NTU for clear coastal waters suitable for coral reef development (Table III). These elevated values indicate a high load of fine suspended sediment in the water column, largely derived from terrestrial erosion and surface runoff within the catchment [12]. High turbidity reduces the availability of underwater light, thereby limiting photosynthesis and impairing coral growth. In addition, the suspended particles that generate turbidity eventually settle onto AR surfaces; on cube-shaped AR, this sediment deposition can smother coral recruits, fill cavities, reduce habitat complexity, and progressively transform the intended hard-substrate habitat into a sediment-dominated environment, ultimately compromising the role of ARs in supporting diverse coral and fish assemblages.

F. Secchi Depth/Water Clarity

The *SD* at Damas Beach ranged from 1.3 to 4.5 m, with a mean of 3.08 m, indicating generally turbid conditions around ARs (Table III). In this semi-enclosed bay, weak near-surface currents (~0.1 m/s) during the southeast monsoon favor the resuspension and local deposition of fine sediments, increasing turbidity and further reducing transparency [9]. Reduced clarity limits light penetration to reef depth, constraining photosynthesis and primary production and influencing the distribution of reef-associated biota [10]. Because coral larval settlement and early growth depend strongly on sufficient light intensity at the substrate surface [13], persistently low *SD* at AR depth is likely to depress coral recruitment and, in turn, the long-term effectiveness of the cube structures as tools for coral reef rehabilitation.

TABLE III. WATER QUALITY IN DAMAS BEACH

Station	Temperature (°C)	Salinity (ppt)	DO (mg/L)	pH	Turbidity (NTU)	*SD* (m)	Current Speed (m/s)	Nitrate (mg/L)	Phosphate (mg/L)
1	25.77	34.35	6.68	7.5	25.23	3.0	0.1	1.811	0.0971
2	24.69	34.52	6.80	7.6	35.78	3.7	0	1.811	0.0971
3	24.75	34.49	6.80	7.3	20.55	4.4	0.1	1.746	0.0947
4	24.82	34.00	6.79	7.4	19.00	4.5	0.1	1.746	0.0947
5	25.33	34.44	6.73	7.8	23.25	1.6	0	1.842	0.3307
6	25.77	34.35	6.68	8	25.23	1.3	0.1	1.842	0.3307

G. Current Speed

The current speed in the waters of Damas Beach during the August 2024 survey ranged from 0 to 0.1 m/s, with a mean of 0.07 ± 0.05 m/s (Table III), indicating very weak flow conditions. This value is well below the commonly cited threshold of 0.5 m/s for moderate coastal currents [2]. Surface currents play an important role in transporting and redistributing suspended sediments, nutrients, and oxygen within the water column [10]. Under such weak-flow conditions, suspended particles are more likely to settle and accumulate around structural features such as cube-shaped ARs, increasing turbidity and reducing local *SD* [10]. Consequently, the combination of low current speeds and high sediment loads at Damas Beach can enhance sediment deposition on reef surfaces and within cube cavities, gradually reducing the effective relief and functional performance of ARs.

H. Nitrate and Phosphate Concentrations

Nitrate concentrations ranged from 1.746 to 1.842 mg/L (mean 1.80 ± 0.04 mg/L), while phosphate ranged from 0.0947 to 0.3307 mg/L (mean 0.17 ± 0.11 mg/L), indicating clear nutrient enrichment at Damas Beach relative to typical open ocean background levels. Higher phosphate values at nearshore stations and lower values offshore suggest dominant terrestrial inputs from the watershed. Such elevated nitrate and phosphate levels can stimulate turf algae and macroalgal growth on AR surfaces, competing with coral recruits for space and light and altering habitat structure. In a monsoon-dominated setting, both terrestrial runoff and upwelling influence nutrient supply [8, 14].

I. Analytical Limitations

Given the limited spatial replication and single-season design, this study focused on descriptive statistics and spatial interpretation to demonstrate the protocol. Formal hypothesis testing and broader inferences are left for future surveys with denser spatial and seasonal coverage.

IV. CONCLUSIONS

This study applies a practical hydro-oceanographic and water quality monitoring workflow to cube-shaped Artificial Reefs (ARs) at Damas Beach, Trenggalek, seven years after deployment (August 2024, southeast monsoon). Temperature (24.69–25.77°C), salinity (34.00–34.52 ppt), Dissolved Oxygen (DO) (6.68–6.80 mg/L), and pH (7.3–8.0) were found within a range generally suitable for coral reef organisms, indicating that background water chemistry is the primary constraint. In contrast, low Secchi Depth (*SD*) (1.3–4.5 m), high turbidity (19.00–35.78 NTU), and very weak current speed (0–0.1 m/s) point to sediment retention conditions that may suppress coral recruitment and reduce habitat quality around the structures. Nutrient enrichment (nitrates 1.746–1.842 mg/L and phosphates 0.0947–0.3307 mg/L) further suggest terrestrial inputs that can promote algal growth and biofouling dominance.

From this study of Damas Bay, the key implication is that AR sustainability is likely limited less by extreme chemical stress and more by the combined effects of turbidity, sediment, and nutrient dynamics. As minimum protocol for data-limited AR sites, standardized measurements of temperature, salinity, DO, pH, turbidity (or *SD*), current speed, and key nutrients are proposed to generate a comparable baseline for routine monitoring. This workflow can be directly adopted by reef managers and local agencies to standardize periodic surveys, support site screening, and evaluate maintenance needs across AR locations. Management actions should prioritize reducing land-based sediment and nutrient inputs, enforcing fishing gear controls near ARs, and conducting periodic inspections/cleaning to remove nets and excess sediments. Future work should extend surveys across seasons and tidal states and integrate biological indicators (coral recruitment and cover, biofouling composition, and fish assemblages) to better link hydro-oceanographic conditions to long-term AR performance.

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