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Research Paper

Tidal and Diel Variability in Physico-Environmental Parameters in Calatagan Marine Protected Area

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Abstract

Mangrove ecosystems are highly dynamic coastal habitats where physicochemical conditions fluctuate in response to tidal and diel (day–night) drivers, yet most monitoring frameworks rarely integrate both temporal dimensions. This study presents the first high-frequency, 24-hour simultaneous assessment of tidal and diel physicochemical and atmospheric parameters across three ecologically distinct coastal stations — a mangrove stand, a tidal channel, and an open sea area with coral reef and seagrass beds — within the Ang Pulo Mangrove Forest of the Calatagan Marine Protected Area (MPA), Batangas, Philippines. Physico-chemical parameters (salinity, temperature, dissolved oxygen, nitrate, depth) and atmospheric variables (air temperature, wind speed, humidity, light intensity) were measured every three hours over a full 24-hour cycle using calibrated field instruments. Statistical analyses employed Kruskal–Wallis tests, Wilcoxon rank-sum pairwise comparisons, Spearman's rho correlation, repeated-measures ANOVA, and multivariate MANOVA. Results revealed significant tidal and diel influences on multiple parameters: nitrate peaked at 119.45 mg/L in the mangrove station during morning low tide, while dissolved oxygen and salinity shifted predictably with tidal influx; air temperature and light intensity peaked at midday, and humidity rose consistently at night. Significant three-way interaction effects among tidal phase, time of day, and station ($p < 0.05$) underscored the spatial and temporal heterogeneity of this coastal system. These findings provide a novel baseline for understanding short-term environmental dynamics in tropical mangrove-coastal systems, introduce a replicable monitoring approach for Marine Protected Areas, and establish an empirical foundation for adaptive, site-specific management strategies in tropical MPAs confronting environmental variability and climate-related pressures.

Keywords: *Calatagan MPA, Diel Cycle, Mangrove Ecosystems, Tidal Variation, Water Quality, Coastal Monitoring*

INTRODUCTION

Mangrove ecosystems are salt-tolerant coastal forests that thrive in sheltered intertidal zones across tropical and subtropical regions (Primavera, 2000). These ecosystems occupy a critical ecological position at the land-sea interface, characterized by extreme environmental gradients shaped by temperature, salinity, wind exposure, solar radiation, flooding regimes, and dissolved oxygen levels — all of which govern species survival, mortality, and distribution (Alongi, 2002).

In the Philippines, mangroves historically covered approximately 500,000 hectares but have declined substantially, primarily due to rapid aquaculture expansion, overexploitation, and coastal development (Basha, 2018; Primavera, 2000). Despite this loss, the Philippines retains 35 recorded mangrove species, with only 18.5% of mangrove areas formally protected, underscoring the urgent need for conservation (Cuenca-Ocay et al., 2025). Mangrove systems remain indispensable to

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coastal communities, providing fuelwood, shellfish, and palms, as well as critical ecosystem services including estuarine fisheries support, water quality regulation, flood mitigation, shoreline stabilization, and biodiversity conservation (Rönnbäck, 1999; Taguiam et al., 2022). Their loss would impose substantial ecological and socioeconomic costs at local, national, and global scales.

Coastal ecosystems are increasingly vulnerable to anthropogenic pressures that degrade water quality. In the Philippines, the Calatagan Mangrove Forest Conservation Park (CMFCP) — a Marine Protected Area (MPA) in Barangay Quilitisan, Calatagan, Batangas — faces growing threats from fishing, resort construction, and recreational water activities (Guntur et al., 2018). These pressures contribute to environmental degradation and compromise water quality monitoring efforts. The absence of systematic, high-frequency monitoring in this area hinders early detection of ecological change and weakens conservation management.

Water quality in mangrove environments is highly sensitive to tidal dynamics and diel cycles. Physicochemical parameters — including salinity, pH, dissolved oxygen, nutrient concentrations, and temperature — fluctuate significantly across tidal phases and times of day, directly influencing mangrove health, species zonation, and ecosystem service delivery (Manju et al., 2011; Khaerudin et al., 2026). However, most existing studies rely on fixed-time or single-station sampling, which fails to capture the fine-scale temporal and spatial variability inherent to tidal mangrove environments (Guntur et al., 2018).

This study addresses these limitations by employing a high-frequency, 24-hour simultaneous monitoring design across three ecologically distinct coastal stations. By explicitly integrating tidal phase and diel cycle as co-drivers, the research generates baseline data critical for evidence-based coastal management. It provides a replicable monitoring protocol for tropical MPAs subject to environmental variability.

Research Objective

This study specifically aims to:

1. Assess how tidal phase and time of day influence atmospheric conditions, including air temperature, wind speed, humidity, and light intensity;
2. Examine how tidal phases affect physico-chemical water parameters — specifically temperature, salinity, depth, dissolved oxygen, and nitrate — across the three sampling stations; and
3. Compare physico-chemical parameters among the mangrove stand, tidal channel, and open sea (coral reef–seagrass) stations to establish a spatial baseline that can support adaptive monitoring and management programs within the Calatagan MPA.

LITERATURE REVIEW

Mangrove ecosystems in the Philippines are among the most biologically productive and ecologically significant coastal habitats in Southeast Asia. Despite a recorded diversity of 35 mangrove species, with Bohol hosting the highest richness, only 18.5% of Philippine mangrove areas are formally protected, and decades of aquaculture expansion, overexploitation, and weak governance have driven substantial declines (Cuenca-Ocay et al., 2025).

Community-based conservation initiatives have demonstrated success in improving fisheries productivity, supporting livelihood diversification, and promoting ecotourism in coastal communities (Creencia & Querijero, 2021), highlighting the dual ecological and socioeconomic value of sustainable mangrove management. Maintaining the ecological integrity of these systems, however, requires a rigorous understanding of the environmental conditions — particularly water quality dynamics — that sustain them.

Water quality is a fundamental determinant of mangrove health, productivity, and species distribution. Research in India demonstrated that salinity, temperature, pH, dissolved oxygen, and nutrient concentrations exhibit significant seasonal and spatial variability in mangrove systems, largely driven by tidal influx and anthropogenic nutrient inputs (Manju et al., 2011; Pawar, 2011).

These findings are directly relevant to the current study. If water quality parameters vary substantially between stations and tidal phases, even within a single day, then relying on single-point or fixed-time sampling is insufficient to characterize environmental conditions in dynamic tidal habitats. This underscores the need for high-frequency, multi-station monitoring, as employed here.

The combined influence of tidal and diel processes on nutrient dynamics represents an emerging research priority in coastal ecology. Khaerudin et al. (2026) demonstrated that tidal–diurnal interactions regulate nitrogen cycling and dissolved oxygen fluctuations in brackish water pond systems, underscoring the importance of capturing both tidal exchange and diel variation in monitoring frameworks. Similarly, Guntur et al. (2018), working in the coastal region of Probolinggo Regency, East Java, showed that physicochemical parameters in mangrove-adjacent waters can exceed established environmental quality standards due to anthropogenic pressures and land-use change.

Their finding that spatial mapping of mangrove distribution provides a basis for identifying priority rehabilitation areas supports the rationale for a multi-station comparative design in the present study. Whereas Guntur et al. (2018) relied on periodic surveys, the current study advances their approach by employing three-hourly measurements over a full 24-hour tidal cycle, enabling finer resolution of environmental dynamics.

Studies on estuarine and coastal systems have further highlighted the sensitivity of water quality parameters to short-term environmental forcing. Zhang et al. (2023) documented the skewed and variable nature of dissolved oxygen and nitrate data in estuarine environments, justifying the use of non-parametric statistical approaches. Schmidt et al. (2019) demonstrated that tidal mixing and stratification drive dissolved oxygen variability in turbid estuaries, while Chen et al. (2020) documented pronounced spatial heterogeneity in water quality across nearshore versus offshore stations in Shenzhen Bay, China.

These findings collectively point to a critical methodological gap: most existing studies in Philippine mangrove systems lack the temporal resolution and multi-habitat spatial design necessary to characterize both tidal and diel dynamics simultaneously. The present study directly addresses this gap within the ecologically significant but understudied Calatagan MPA.

RESEARCH METHOD

The study was conducted in the Calatagan Mangrove Forest Conservation Park (CMFCP), a Marine Protected Area in Barangay Quilitisan, Calatagan, Batangas, Philippines (N 13°53′, E 120°37′). Locally known as *Ang Pulo*, the CMFCP encompasses approximately 7–7.5 hectares of mangrove forest (Coral Triangle Initiative, 2014).

Three sampling stations were established to represent distinct coastal ecosystem types and to capture spatial heterogeneity in environmental dynamics, consistent with a comparative multi-habitat design: (1) a tidal channel (13.91581°N, 120.622686°E), representing a confined, tidally flushed corridor; (2) an open sea area with coral reef and seagrass beds (13.885461°N, 120.633113°E), representing an offshore, wave-exposed habitat; and (3) a mangrove stand (13.915331°N, 120.622327°E), representing the vegetated intertidal zone. Station selection was based on ecological representativeness, accessibility, and differential exposure to tidal influence. All three stations are used consistently throughout this study.

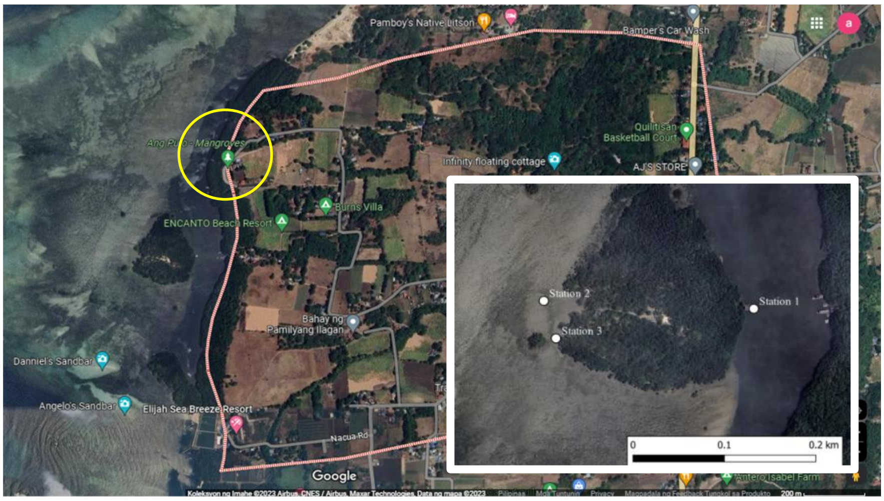

Figure 1. Google satellite image of the Ang Pulo mangrove forest in Barangay Quilitisan, Calatagan, Batangas, showing the three sampling stations.

Data Collection Techniques

A short-term diurnal monitoring design was employed to assess water quality dynamics across tidal phases and times of day within a continuous 24-hour cycle. Sampling was conducted from 9:00 AM on 6 June 2025 to 9:00 AM on 7 June 2025. Measurements were taken every three hours, a frequency selected to align with semidiurnal tidal transitions (occurring approximately every 12 hours, with high-to-low transitions every six hours) and to capture diurnal variation in atmospheric and biological processes.

A three-hour interval ensured at least two measurements per tidal phase. It resolved shifts across the morning, noon, evening, and nighttime periods, consistent with the approach of Khaerudin et al. (2026). This interval provided sufficient temporal resolution to detect short-term fluctuations while remaining logistically feasible for continuous field deployment by a small research team.

At each station, all parameters were measured in triplicate to minimize instrument error and ensure data reliability. Instruments were rinsed with distilled water between stations to prevent cross-contamination. GPS coordinates and field photographs were recorded at each sampling point to ensure spatial accuracy and reproducibility. The sampling sequence was standardized across stations to reduce procedural bias. The design was explicitly exploratory and intended to generate a quantitative baseline for future long-term monitoring rather than to provide seasonal or interannual generalizations.

Sampling Methods

Atmospheric conditions — wind speed, air temperature, light intensity, and relative humidity — were recorded using a calibrated multifunction light meter (PCE-EM 888). Water quality parameters — temperature, dissolved oxygen, nitrate, pH, Oxidation-Reduction Potential (ORP), and barometric pressure — were measured using an Aqua TROLL 600 Multiparameter Sonde. Hydrological characteristics were assessed through water transparency (Secchi disk), depth (graduated stick), and salinity (handheld refractometer). All instruments were calibrated according to manufacturer specifications prior to and during field deployment, including standard solution calibration for dissolved oxygen and pH, and distilled water zeroing for the refractometer.

Data Analysis Procedures

Given the non-normality of the environmental data, as confirmed by Shapiro–Wilk tests ($p <$

0.05 for most variables), non-parametric statistical procedures were applied throughout. The Kruskal–Wallis H-test was used to evaluate differences in atmospheric and water quality parameters across tidal phases (high, low, rising, falling) and times of day (morning, noon, evening, night) at the univariate level. Wilcoxon rank-sum pairwise comparisons with Bonferroni correction were used to identify specific phase contrasts that drive the overall significance.

Spearman's rho (ρ) was computed to assess monotonic associations between tidal phase, time of day, and measured parameters, as this rank-based correlation coefficient is appropriate for non-normal, ordinal, and environmental data. Repeated-measures ANOVA was employed to assess within-station temporal variation in water quality parameters measured across time intervals. A multivariate analysis of variance (MANOVA, using Pillai's Trace) was applied to assess the simultaneous effects of time of day, station, tidal phase, and their interactions on the suite of water quality parameters.

All analyses were conducted using JASP (version 2.6.44) and Microsoft Excel. Descriptive statistics (mean ± standard deviation) were computed for all parameters. The significance threshold was set at $\alpha = 0.05$ for all tests. This analytical framework enabled a comprehensive, statistically rigorous characterization of tidal and diel dynamics across the three study stations.

Validity and Reliability Measures

Instrument calibration, triplicate measurements, and rinsing protocols ensured measurement accuracy and minimized systematic error. Documentation through photographs and GPS coordinates supported spatial precision and reproducibility. While the one-day design constrained temporal generalizability, this approach was justified as an exploratory baseline study aligned to tidal and diurnal cycles, maximizing ecological relevance within logistical constraints. Findings provide foundational data to inform extended monitoring programs.

FINDINGS AND DISCUSSION

Atmospheric Parameters by Tidal Phase and Time of Day

The Kruskal–Wallis test revealed that wind speed ($p < 0.001$) and light intensity ($p = 0.033$) varied significantly across tidal phases, while air temperature ($p = 0.498$) and relative humidity ($p = 0.283$) did not (Table 1). By contrast, time of day significantly influenced air temperature ($p < 0.001$), light intensity ($p < 0.001$), and relative humidity ($p < 0.001$), but not wind speed ($p = 0.545$). These differential patterns indicate that wind dynamics in this mangrove-coastal system are more responsive to tidal forcing. At the same time, thermal and moisture conditions are primarily governed by solar-driven diel cycles.

Table 1. Kruskal–Wallis Test Results for Tide and Time Effects on Atmospheric Parameters

Condition	Wind Speed	Air Temperature	Light Intensity (Lux)	Relative Humidity
Tide	**< .001**	0.498	**0.033**	0.283
Time of Day	0.545	**< .001**	**< .001**	**< .001**

Note: Values in bold are statistically significant ($p < 0.05$). Kruskal–Wallis H-test applied.

Pairwise Wilcoxon rank-sum tests (Table 2) indicated that wind speed differed significantly between falling tide and high tide ($W = -4.82$, $p = 0.004$), falling tide and rising tide ($W = -4.75$, $p = 0.004$), and low tide and rising tide ($W = -3.95$, $p = 0.027$). Light intensity was significantly higher during falling tide compared to high tide ($W = 4.862$, $p = 0.003$). Relative humidity was significantly lower during falling tide than during high tide ($W = -3.994$, $p = 0.025$).

These findings are consistent with tidal modulation of the coastal microclimate: reduced water cover during the ebb exposes sediments and vegetation to solar radiation, thereby enhancing evaporation and altering local air circulation patterns (Jacob & Stanev, 2017; Ray & Susanto, 2019). The observation that wind speed increases during falling and low-tide phases likely reflects tide-driven changes in pressure gradients and surface roughness over exposed intertidal flats, which in turn modulate water mixing, dissolved oxygen distribution, and nutrient cycling in the adjacent mangrove waters (Barnett et al., 2020).

Table 2. Pairwise Wilcoxon Rank-Sum Test Results for Tidal Phase Comparisons of Atmospheric Parameters

Parameter	Comparison	W	p	Interpretation
Wind Speed	Falling Tide vs High Tide	**−4.82**	**0.004**	**Significant**
	Falling Tide vs Low Tide	−2.09	0.453	Not Significant
	Falling Tide vs Rising Tide	**−4.75**	**0.004**	**Significant**
	High Tide vs Low Tide	3.04	0.138	Not Significant
	High Tide vs Rising Tide	−1.42	0.746	Not Significant
	Low Tide vs Rising Tide	**−3.95**	**0.027**	**Significant**
Air Temperature	Falling Tide vs High Tide	3.059	0.134	Not Significant
	Falling Tide vs Low Tide	1.228	0.821	Not Significant
	Falling Tide vs Rising Tide	0.566	0.978	Not Significant
	High Tide vs Low Tide	−1.289	0.799	Not Significant
	High Tide vs Rising Tide	−0.419	0.991	Not Significant
	Low Tide vs Rising Tide	0.962	0.905	Not Significant
Light Intensity (Lux)	Falling Tide vs High Tide	**4.862**	**0.003**	**Significant**
	Falling Tide vs Low Tide	2.696	0.225	Not Significant
	Falling Tide vs Rising Tide	3.632	0.050	Not Significant
	High Tide vs Low Tide	−1.464	0.729	Not Significant
	High Tide vs Rising Tide	−0.782	0.946	Not Significant
	Low Tide vs Rising Tide	0.000	1.000	Not Significant
Relative Humidity	Falling Tide vs High Tide	**−3.994**	**0.025**	**Significant**
	Falling Tide vs Low Tide	0.189	0.999	Not Significant
	Falling Tide vs Rising Tide	−1.321	0.787	Not Significant
	High Tide vs Low Tide	2.007	0.487	Not Significant
	High Tide vs Rising Tide	0.120	1.000	Not Significant
	Low Tide vs Rising Tide	−1.164	0.844	Not Significant

Note: Bold values indicate statistical significance ($p < 0.05$). Bonferroni correction applied for multiple comparisons.

Spearman correlation analysis (Table 3) confirmed that tidal phase had negligible associations with atmospheric parameters ($r = 0.225$ for wind speed; $r = 0.017$ for air temperature; $r = -0.003$ for light intensity; $r = -0.015$ for relative humidity; all non-significant). In contrast, time of day showed strong, significant correlations with air temperature ($r = -0.645$, $p < 0.001$), light intensity ($r = -0.739$, $p < 0.001$), and relative humidity ($r = 0.754$, $p < 0.001$). Peak air temperature reached 34.7°C at noon, and peak light intensity was 9,886.79 lux, while the lowest values occurred at night across all stations.

These patterns reflect canonical diel forcing by solar radiation, consistent with Kimball (1986) and more recent work documenting that mangrove canopy structure moderates midday temperatures while preserving nocturnal humidity (Lopez et al., 2025; Jurado et al., 2025; Lutsko, 2021). The ecological implication is that midday thermal peaks, uncoupled from tidal phase, create periods of elevated evaporation and potential salinity stress in shallow mangrove waters — conditions particularly challenging for less tolerant mangrove associates such as *Rhizophora spp.*

Table 3. Spearman's Rho Correlation of Atmospheric Parameters with Tidal Phase and Time of Day

Condition	Wind Speed	Air Temperature	Light Intensity (Lux)	Relative Humidity
Tide	0.225 Weak	0.017 Very Weak	−0.003 Negligible	−0.015 Negligible
Time of Day	0.150 Very Weak	**−0.645*** Strong Negative**	**−0.739*** Strong Negative**	**0.754*** Strong Positive**

Note: *** p < .001. Non-significant correlations are not asterisked.

Water Quality Parameters: Temporal and Tidal Variation

Repeated-measures ANOVA revealed significant temporal variation in dissolved oxygen (F(2) = 9.87, p = 0.028), DO saturation (F(2) = 7.12, p = 0.048), nitrate concentration (F(2) = 41.2, p = 0.002), nitrate in millivolts (F(2) = 140, p < 0.001), and salinity (F(2) = 11, p = 0.024) across sampling times (Table 4). Water depth, pH, pH (mV), ORP, water temperature, barometric pressure, and Secchi disk reading did not differ significantly across time (all p > 0.05). These results indicate that the most ecologically significant water quality parameters — oxygen availability and nutrient concentrations — are highly responsive to temporal dynamics within the 24-hour monitoring period, consistent with Zhang et al. (2023) and Li et al. (2020).

Table 4. Repeated-Measures ANOVA Results for Water Quality Parameters Across Sampling Times

Water Parameter	df	F	p-value	Interpretation
Water Depth	2	4.27	0.102	Not Significant
Dissolved Oxygen (mg/L)	2	**9.87**	**0.028**	**Significant**
DO Saturation (%)	2	**7.12**	**0.048**	**Significant**
Nitrate NO_3-N (mg/L)	2	**41.2**	**0.002**	**Significant**
Nitrate (mV)	2	**140**	**< .001**	**Significant**
pH	2	0.996	0.446	Not Significant
pH (mV)	2	2.81	0.173	Not Significant
Oxidation-Reduction Potential	2	1.63	0.303	Not Significant
Temperature (°C)	2	2.44	0.203	Not Significant
Barometric Pressure (mmHg)	2	0.0171	0.983	Not Significant
Secchi Disk Reading (cm)	2	1.87	0.267	Not Significant
Salinity (ppt)	2	**11.0**	**0.024**	**Significant**

Note: Bold values indicate statistical significance (p < 0.05). Sphericity assumed; corrections applied if violated.

Multivariate MANOVA (Table 5) confirmed significant simultaneous effects of time of day (Pillai's Trace = 1.586, F(24, 46) = 7.35, p < 0.001), station (Pillai's Trace = 1.166, F(24, 46) = 2.68, p = 0.002), and tidal phase (Pillai's Trace = 1.742, F(36, 72) = 2.77, p < 0.001). Critically, the time-of-day × tidal phase interaction was also significant (Pillai's Trace = 0.840, F(12, 22) = 9.6, p < 0.001), as was the three-way interaction of time of day × station × tidal phase (Pillai's Trace = 0.997, F(24, 46) = 1.9, p = 0.03).

The significance of these interaction terms is ecologically critical: they indicate that the influence of tidal phase on water quality is not uniform across times of day or habitat types.

Mangrove, seagrass, and tidal channel stations each respond differently to tidal forcing at different times, confirming that fixed-time, single-station monitoring would substantially misrepresent true environmental conditions in this system. These findings are consistent with Chen et al. (2020), who documented comparable spatial heterogeneity in water quality across contrasting nearshore and offshore stations.

Table 5. MANOVA Results for the Effects of Time of Day, Station, Tidal Phase, and Their Interactions on Water Quality Parameters

Effect	Pillai's Trace	F	df1	df2	p	Interpretation
Time of Day	**1.586**	**7.35**	24	46	**< .001**	**Significant**
Station	**1.166**	**2.68**	24	46	**0.002**	**Significant**
Tide	**1.742**	**2.77**	36	72	**< .001**	**Significant**
Time of Day × Station	1.631	1.43	48	100	0.066	Not Significant
Time of Day × Tide	**0.840**	**9.6**	12	22	**< .001**	**Significant**
Station × Tide	2.172	1.28	72	162	0.104	Not Significant
Time of Day × Station × Tide	**0.997**	**1.9**	24	46	**0.030**	**Significant**

Note: Pillai's Trace is reported as the robust multivariate test statistic. Bold indicates $p < 0.05$.

Spearman Correlation Between Tidal Phase, Time of Day, and Water Quality Parameters

Spearman's rho analysis (Table 6) showed that tidal phase was significantly and negatively correlated with dissolved oxygen ($\rho = -0.527$, $p < 0.01$) and DO saturation ($\rho = -0.477$, $p < 0.01$), indicating that higher tidal stages are associated with lower oxygen levels. This inverse relationship between tide height and dissolved oxygen likely reflects tidal dilution of oxygen-rich surface waters by deeper, oxygen-depleted marine water during tidal inundation, a mechanism documented in mangrove systems by Schmidt et al. (2019).

Tidal phase was strongly and positively correlated with salinity ($\rho = 0.476$, $p < 0.001$), consistent with saline marine water inundation during high tide. Moderate negative correlations were observed between tidal phase and ORP ($\rho = -0.333$) and Secchi disk reading ($\rho = -0.348$), suggesting that high tide reduces light penetration and promotes oxidizing conditions, potentially through increased turbidity and sediment resuspension (Zhao et al., 2025).

Time of day was significantly and negatively correlated with water temperature ($\rho = -0.553$, $p < 0.001$) and barometric pressure ($\rho = -0.459$, $p < 0.01$). The negative correlation between time of day and temperature reflects afternoon cooling following peak midday solar input, consistent with the diel thermal cycle. The moderate positive correlations of time with pH ($\rho = 0.328$) and salinity ($\rho = 0.352$) may reflect photosynthesis-driven increases in pH during daylight and evaporation-driven salinity concentration during peak solar periods (Huang et al., 2020). These patterns underscore the importance of accounting for both tidal phase and time of day when interpreting physicochemical data from this system.

Table 6. Spearman's Rho Correlation Matrix for Tidal Phase, Time of Day, and Water Quality Parameters

Conditions	WD	DO	DO sat (%)	N (mg/L)	N (mV)	pH	pH (mV)	ORP	Temp (°C)	BP (mmHg)	SDR (cm)	S (ppt)
Tide	0.007	**−0.527*** **	**−0.477*** **	0.251	−0.207	**−0.295* **	−0.253	**−0.333* **	−0.161	−0.320	**−0.348* **	**0.476*** **
Time of Day	−0.189	0.026	0.029	**−0.414** **	0.200	**−0.292* **	**0.328* **	0.227	**−0.553*** **	**−0.459*** **	−0.267	**0.352** **

Note: WD = Water Depth; DO = Dissolved Oxygen; N = Nitrate; ORP = Oxidation-Reduction Potential;
BP = Barometric Pressure; SDR = Secchi Disk Reading; S = Salinity. * $p < .05$, ** $p < .01$, *** $p < .001$.

Tidal Phase Effects on Water Parameters

Tidal phase significantly influenced the physicochemical properties of coastal waters, particularly salinity, nitrate concentration, and dissolved oxygen saturation. Salinity reached its peak during high tide (40 ppt across all three stations), with the lowest value recorded during low tide at the mangrove station (mean = 31.5 ppt).

This 8.5 ppt range within a single tidal cycle demonstrates the substantial salinity stress that mangrove organisms must tolerate, with implications for species composition and zonation across the three habitat types. Water depth followed the expected tidal pattern, with the highest level (76.5 cm) observed at the seagrass station during high tide and the lowest depths during ebb tide, particularly in the geomorphologically confined mangrove zone, where restricted water exchange concentrates ecological stressors.

DO saturation decreased from 74.25% during high tide to 58.63% at low tide in the mangrove area. This 15.6 percentage-point reduction in oxygen availability during low tide is ecologically significant: it approaches hypoxic thresholds that can limit aerobic microbial activity, stress benthic invertebrates, and suppress fish use of the mangrove fringe (Schmidt et al., 2019). The mechanism likely involves tidal pumping: as water withdraws, restricted exchange between the mangrove water column and the oxygenated open sea reduces replenishment of dissolved oxygen, while concurrent decomposition of organic matter by sediment microbes continues to consume available oxygen.

The Kruskal–Wallis test confirmed that nitrate was significantly affected by time of day ($\chi^2 = 14.16$, $p < 0.001$), DO ($\chi^2 = 12.78$, $p = 0.002$), and salinity ($\chi^2 = 21.65$, $p < 0.001$), underscoring the dual influence of tidal and diel cycles on water chemistry. Non-parametric methods were applied as validated by Shapiro–Wilk tests confirming non-normal distributions ($p < 0.05$) for most variables (Zhang et al., 2023).

Diurnal Variation in Water Parameters

Pronounced diel fluctuations were observed in nitrate concentration, dissolved oxygen, and water temperature across the three study stations. Nitrate levels were highest in the morning (119.45 mg/L at the mangrove station), declined by noon (102.72 mg/L), and were lowest at night (88.71 mg/L). The elevated morning nitrate peak likely reflects overnight accumulation from the decomposition of organic matter in mangrove sediments, with reduced uptake during darkness, when photosynthesis is absent, and denitrification may be suppressed at lower temperatures.

The subsequent midday decline is consistent with phytoplankton and benthic algae uptake driven by peak light availability, as well as microbial denitrification under warming temperatures. This pattern parallels findings from Castro and Dimalanta (2025) and Jurado et al. (2025) in tropical estuarine environments.

DO concentrations were highest at night in the coral reef (5.62 mg/L) and seagrass (5.56 mg/L) stations and lowest at noon in the mangrove station (4.69 mg/L). This counterintuitive nocturnal oxygen peak can be explained by convective cooling of the water surface at night, which enhances atmospheric gas exchange and increases oxygen solubility.

Additionally, reduced community respiration under cooler nocturnal conditions and decreased photosynthetic oxygen consumption relative to net community exchange can produce modest oxygen accumulation. Water temperature peaked at noon, particularly at the seagrass station (36.33°C), corresponding to maximum solar radiation. This near-lethal thermal peak for many seagrass species and coral-associated organisms underscores the ecological significance of diel temperature dynamics, independent of tidal forcing.

These results collectively demonstrate that water quality monitoring conducted at a single fixed time of day — a common practice in many MPA assessments — would substantially misrepresent the range of conditions experienced by organisms within the system. Time-integrated, multi-point monitoring is therefore strongly recommended for management-relevant ecological assessments in Philippine coastal MPAs.

CONCLUSIONS

This study investigated tidal and diel variability in physico-environmental parameters across three ecologically distinct coastal stations — a mangrove stand, a tidal channel, and an open-sea area with coral reefs and seagrass beds — within the Ang Pulo Mangrove Forest, Calatagan MPA, Philippines, over a continuous 24-hour, high-frequency monitoring period.

The primary findings demonstrate that: (1) wind speed and light intensity were significantly influenced by tidal phase, while air temperature, relative humidity, and light intensity varied significantly with time of day, indicating that atmospheric dynamics in this mangrove-coastal system are governed by a combination of tidal forcing and solar-driven diel cycles; (2) dissolved oxygen, DO saturation, nitrate, and salinity showed significant temporal variation across the 24-hour monitoring period, with DO declining during low tide in the mangrove station and nitrate peaking in the morning across all stations; (3) MANOVA confirmed significant simultaneous effects of time of day, station, tidal phase, and their interactions on the suite of water quality parameters, with a significant three-way interaction indicating that habitat type modulates how tidal and diel forcing influences water chemistry; and (4) Spearman correlations confirmed that tidal phase is strongly negatively correlated with dissolved oxygen and positively correlated with salinity, while time of day is strongly negatively correlated with water temperature and barometric pressure.

These findings are directly grounded in the data collected and are confined to the spatial and temporal scope of this study: three stations over one 24-hour period during June 2025. They cannot be generalized to seasonal or interannual patterns, nor to mangrove systems outside the Calatagan MPA without further investigation. The concurrent significance of tidal and diel drivers across atmospheric and water quality parameters demonstrates that neither driver alone is sufficient to characterize environmental variability in this system. Monitoring programs that integrate both temporal dimensions at an adequate frequency are therefore essential for ecologically meaningful assessment.

This study makes several significant contributions to the understanding of coastal mangrove ecosystems and environmental monitoring in tropical Marine Protected Areas. First, it provides the first simultaneous, high-frequency baseline characterization of both tidal and diel physicochemical dynamics across three contrasting coastal habitat types — mangrove stand, tidal channel, and open-sea coral reef–seagrass area — within the Calatagan MPA, filling a critical data gap for this ecologically significant yet understudied site. Second, the significant three-way interaction among time of day, station, and tidal phase ($p = 0.030$) demonstrates that habitat type modulates how tidal and diel forcing shape water chemistry. This finding challenges single-station or fixed-time monitoring approaches and advances understanding of spatiotemporal heterogeneity in tropical mangrove-coastal systems.

Third, the elevated morning nitrate peak (119.45 mg/L) and the pronounced diel and tidal fluctuations in dissolved oxygen and salinity provide quantitative thresholds relevant to assessing ecological stress in mangrove and seagrass habitats under variable tidal regimes. Fourth, this study introduces and validates a replicable three-hourly multi-station monitoring protocol that is logistically feasible for small research teams and directly applicable to comparable Philippine coastal MPAs facing environmental variability and climate-related pressures. Collectively, these contributions advance the methodological and empirical foundation for evidence-based adaptive management of tropical coastal ecosystems and offer a transferable monitoring framework for MPA managers across Southeast Asia.

LIMITATION & FURTHER RESEARCH

This study provides high-frequency insights into tidal and diel variability in a mangrove-coastal system; however, several limitations should be considered. Data were collected over a single 24-hour period, capturing fine-scale, short-term variability but not accounting for seasonal, monsoonal, or interannual influences that affect tropical coastal environments. Spatial coverage was limited to three representative stations, and finer microhabitat heterogeneity within each ecosystem type may not have been fully resolved.

Furthermore, the study focused on physico-chemical and atmospheric parameters; biological and biogeochemical processes that drive observed patterns — including primary productivity, microbial respiration, and sediment–water nutrient exchange — were not directly measured and remain important avenues for future investigation.

Future research should extend high-frequency monitoring across longer temporal scales and multiple seasons to capture climate-driven variability. Integrating biological indicators, sediment and porewater nutrient fluxes, and vertical water profiling would improve mechanistic understanding of tidal and diel processes. Expanding spatial coverage and linking environmental variability to ecosystem service provisioning would further strengthen adaptive management frameworks for tropical MPAs in the Philippines and the broader Southeast Asian region.

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