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Spatiotemporal Assessment and Index-Based Evaluation of Coastal Water Quality at Selected Beaches in Southern Sri Lanka

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Abstract

The coastline of Sri Lanka plays an important role in shaping the socio-economic development through fisheries, tourism, and ecosystem services. However, the anthropogenic influence and the absence of systematic water quality assessments create serious challenges to coastal sustainability. This study evaluates the coastal water quality of Unawatuna, Mirissa and Polhena beaches through a spatiotemporal analysis and develops a Coastal Water Quality Index (CWQI). A total of 152 samples were collected across 19 sites between May to December 2023 and analyzed for pH, salinity, EC, TDS, DO, turbidity, TSS, phosphate, nitrate, and nitrite. Results were compared against ASEAN and regional marine water quality standards. Most of the parameters were within acceptable limits except for phosphate, highlighting the anthropogenic nutrient inputs. PERMANOVA and NMDS revealed spatial consistency in Unawatuna and Mirissa, while Polhena exhibited significant spatial variation, particularly in DO levels. October to November showed water quality deviations across all sites, linked to intermonsoon effects. CWQI results ranged from 14 (excellent) to 118 (poor), 14 (excellent) to 74 (good) and 17 (excellent) to 124 (poor) in Unawatuna, Mirissa and Polhena, respectively. Although overall water quality remained generally stable, an upward trend of CWQI values indicates a decline in water quality. These findings highlight the urgent need for monitoring and integrated coastal zone management strategies to maintain ecological resilience and support sustainable policy development.

Introduction

Coastal regions are among the most dynamic and economically valuable environments, serving as hubs for cultural exchange, global trade, and ecological integrity (Senevirathna et al., 2018; Veidemane et al., 2024). Globally, these areas host diverse ecosystems such as lagoons, estuaries, mangroves, salt marshes, sand dunes, and wetlands, which provide critical ecosystem services including nutrient cycling, pollutant detoxification, food production, shoreline protection, and recreational opportunities (Barbier et al., 2011; Lu et al., 2018; Nianthi & Shaw, 2015; Purcell et al., 2020). The integrity and quality of coastal waters are fundamental

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to sustaining these services and ensuring the productivity of marine and estuarine ecosystems (Jha et al., 2015).

Sri Lanka, with its 1,720 km coastline, is endowed with highly diverse and unique coastal habitats, including lagoons, estuaries, mangroves, beaches, and salt marshes. These ecosystems support rich biodiversity, provide nursery grounds for ecologically and commercially important species, and sustain a wide range of social and economic activities (Karunathilake, 2003; Rupasinghe & Perera, 2006; Sellamuttu et al., 2011). As a result, Sri Lanka's coastal belt is of exceptional environmental, social, and economic value (Senevirathna et al., 2018).

However, these coastal environments worldwide are under severe pressure from urbanization, industrial expansion, tourism-driven land conversion, pollution, and overexploitation of natural resources (Gössling & Dolnicar, 2023; Zahedi, 2008). In Sri Lanka, rapid urban growth, inadequate waste management, and nutrient enrichment have contributed to widespread coastal water pollution and associated public health risks (Abeysekera, 1991; Ileperuma, 2000). Key pollutants include oils, heavy metals, nutrients, and organic matter, which increase turbidity, reduce dissolved oxygen, and accelerate eutrophication, often triggering harmful algal blooms (Mishra et al., 2023; Siriwardana et al., 2024b; Tian & Xie, 2025). Human and aquaculture waste, together with deforestation, further exacerbate nutrient loading, intensifying ecological degradation (Lu et al., 2018).

Despite these threats, Sri Lanka lacks a systematic, long-term coastal water quality monitoring framework. Most existing studies are often fragmented, short-term, and skewed toward freshwater systems rather than coastal ecosystems (Corea, 2019; Hsieh et al., 2021). The absence of comprehensive datasets constrains the ability of policymakers to identify pollution hotspots, assess long-term ecological changes, and anticipate risks such as biodiversity loss and harmful algal blooms (Manage et al., 2022). Limited standardization and inadequate resources for coastal monitoring further undermine evidence-based, effective coastal management and conservation planning.

The southern coast of Sri Lanka hosts some of the nation's most prominent tourist destinations, including Mirissa, Polhena, and Unawatuna, which are globally recognized for recreational activities such as snorkeling, whale watching, and beach tourism. These sites harbor coral reefs, seagrass beds, and other critical habitats that enhance fisheries productivity, biodiversity, and shoreline protection (Berg et al., 1998). For instance, Polhena's shallow lagoon is sheltered by an offshore reef, creating both safe recreational conditions and high biodiversity. However, increasing tourism, wastewater discharge, and poor solid waste management have heightened risks of microbial and nutrient contamination in these areas (Saja et al., 2021). Previous investigations have reported elevated phosphate concentrations in Unawatuna (0.117±0.008 mg/L), Mirissa (0.130±0.003 mg/L) (Manage et al., 2022), and Polhena (0.110±0.1 mg/L) (Manikarachchi et al., 2014), all of which exceed the ASEAN guideline threshold of 0.015 mg/L. Similarly, nitrite concentration in Polhena (0.05±0.01 mg/L) (Manikarachchi et al., 2014) were found to be approaching the ASEAN guideline maximum of 0.055 mg/L. These findings highlight clear signs of nutrient enrichment, underscoring the urgent need for continuous monitoring of water quality parameters on these beaches. In addition to anthropogenic pressures, Mirissa, Polhena and Unawatuna are located within erosion prone coastal zones that are highly vulnerable to sea-level rise and extreme weather events, which can alter salinity regimes, modify vegetation composition, and diminish overall ecosystem resilience (Garcin et al., 2008; Mathiventhan et al., 2022).

Given these challenges, there is an urgent need for site-specific, systematic coastal water quality assessments to inform sustainable management of Sri Lanka's southern coastal ecosystems. This study aimed to (i) assess spatiotemporal variation of water quality in three southern beaches using multivariate methods, (ii) develop a Coastal Water Quality Index (CWQI) based on physicochemical indicators, and (iii) provide management implications for Sri Lanka's coastal policy. The findings aim to provide robust baseline data to support ecological conservation, sustainable tourism practices and evidence-based policy development for the protection of Sri Lanka's coastal environment.

Materials and methods

1. Study area

The study was carried out at three beaches in the southern province of Sri Lanka, Unawatuna (7 sites), Mirissa (6 sites), and Polhena (6 sites). Geographical coordinates were recorded for each site, and maps were prepared (Fig. 1 and Table 1).

Table 1 GPS Coordinates of sampling locations of Unawatuna (7), Mirissa (6) and Polhena (6)

Beach	Sampling Location	GPS Coordinates		Beach	Sampling Location	GPS Coordinates	
		N	E			N	E
Unawatuna	UV1	6.00642	80.24439	Mirissa	MR4	5.94386	80.45999
Unawatuna	UV2	6.00675	80.24394	Mirissa	MR5	5.94320	80.46109
Unawatuna	UV3	6.00754	80.24405	Mirissa	MR6	5.94221	80.46208
Unawatuna	UV4	6.00830	80.24498	Polhena	PLH1	5.93623	80.52497
Unawatuna	UV5	6.00895	80.24600	Polhena	PLH2	5.93606	80.52543
Unawatuna	UV6	6.00916	80.24863	Polhena	PLH3	5.93585	80.52611
Unawatuna	UV7	6.00777	80.25075	Polhena	PLH4	5.93635	80.52684
Mirissa	MR1	5.94386	80.45583	Polhena	PLH5	5.93683	80.52811
Mirissa	MR2	5.94440	80.45770	Polhena	PLH6	5.93728	80.52857
Mirissa	MR3	5.94434	80.45864				

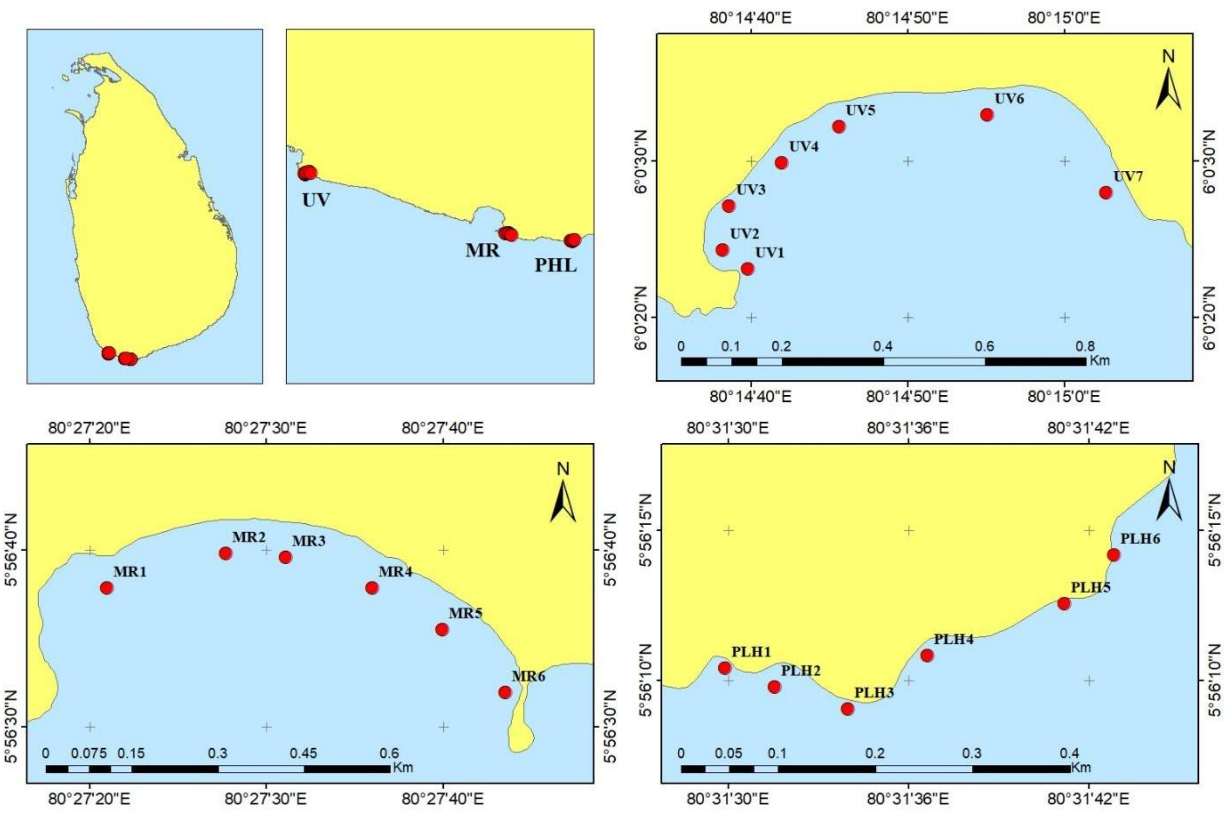


Fig. 1 Location of the study area in southern Sri Lanka. (Top left) Map of Sri Lanka with the study region highlighted. (Top right) Sampling sites in Unawatuna (UV, 7 sites). (Bottom left) Sampling sites in Mirissa (MR, 6 sites). (Bottom right) Sampling sites in Polhena (PHL, 6 sites). Latitude and longitude of sampling points are shown.

2. Sampling

Samples were collected for 8 months period, from May to December, 2023 according to the National Field Manual for the Collection of Water-Quality Data: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 9, (Lane & Fay, 2015). The polypropylene vessels were soaked in the 1:4 nitric acid for a few days and then rinsed with distilled water. The sampling vessels were sealed immediately after sample collection. Sampling was conducted monthly from May to December 2023, covering the south-west monsoon, intermonsoon, and north-east monsoon seasons to capture both spatial and temporal variation in coastal water quality. In total, 152 water samples were collected during the study (19 sites × 8 months). Each site was sampled once/month, with duplicate measurements for in-situ parameters to ensure accuracy. The sampling locations were selected to represent the environmental conditions, bathing and recreation zones where tourism and local activities influence water quality.

3. Water quality parameters

The physical parameters such as pH, salinity, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO) and turbidity were measured at the site using a DO meter (HANNA, Romania), a multimeter (HANNA, Romania) and a turbidity meter (LOVIBOND, Germany). Total suspended solids (TSS) were determined by filtering 1 L of seawater through pre-dried and pre-weighed filter papers (Millipore GF/C) and washing them with Milli-Q water to remove salt content. The chemical parameters such as phosphate (PO_4^{3-}), nitrate (NO_3^-), and nitrite (NO_2^-) were analyzed using standard methods from Standard Methods for Examination of Water and Wastewater (Rice et al., 2019). This study did not include biological parameters because of challenges in sample preservation and logistics; instead, the focus was placed on physicochemical indicators that directly reflect coastal water quality conditions.

4. Statistical analysis

The data were statistically analyzed using R software (R Foundation, 2024). Data were first tested for normality using the Shapiro-Wilk test. Because most variables did not follow a normal distribution, differences were assessed using permutational multivariate analysis of variance (PREMANOVA), with “location” and “month” as fixed factors. This provided a statistical test of both spatial and temporal effects on water quality. To complement the PERMANOVA results, non-metric multidimensional scaling (NMDS) was applied to visualize clustering patterns among sites and months based on Bray-Curtis similarity of standardized data.

5. Coastal water quality index (CWQI) development

The CWQI was calculated by using the weighted arithmetic index (WAI) method. Individual water quality parameters are multiplied by a weighting factor found for each variable and summed using the simple arithmetic mean formula in accordance with this method (Gonul et al., 2023). Subsequently, Sri Lanka does not have a national coastal water quality guideline. Thus, the ASEAN water quality criteria (AusAID, 2008) Indian marine water quality standards were used in defining threshold limits. Calculation of CWQI is carried out using equation 1 (eq. 1) as follows.

$$WQI = \frac{\sum_{i=1}^{n} w_i q_i}{\sum_{i=1}^{n} w_i} \quad \text{(eq. 1)}$$

Where n is the number of variables, w_i is the relative weight of the i^{th} variable, and q_i is the water quality rating of the i^{th} variable. The value of qi computed using equations 2 and 3 (eq. 2 & eq. 3) is given below.

Equation 2 was used for the parameters, which require lower concentrations for better water quality.

$$q_i = 100\left[\frac{S_i - V_i}{S_i - V_{id}}\right] \quad \text{(eq. 2)}$$

Equation 2b was used for parameters for which higher concentrations are needed for better water quality.

$$q_i = 100\left[\frac{V_i - V_{id}}{S_i - V_{id}}\right] \quad \text{(eq. 3)}$$

Where V_i is the detected value of the i^{th} variable, S_i is the standard allowable value of the i^{th} variable, and V_{id} is the ideal value of the i^{th} variable in sea water. All the ideal values (V_{id}) are accepted as zero for sea water except DO and pH (Gonul et al., 2023).

The resulting CWQI values were categorized as, <50 = Excellent, 50–100 = Good, 100–200 = Poor, 200–300 = Very Poor and 300 = Unsuitable for coastal use (Gonul et al., 2023).

Literature shows that WQI methods typically allow flexibility in selecting which water quality parameters to include, based on data availability, environmental context, and monitoring objectives (Anastasopoulos & Akratos, 2025). In this study, DO and pH were selected for ecosystem health, turbidity for clarity and PO_4^{3-}, NO_3^-, and NO_2^- concerning eutrophication risk.

Results and discussion

1. Descriptive statistics

Limited research has been conducted to evaluate the coastal water quality of Unawatuna, Mirissa and Polhena. Table 2 summarizes the descriptive statistics of the measured water quality parameters. The coastal water quality of the selected beaches, Unawatuna, Mirissa, and Polhena, exhibited overall consistency, with some variations in key parameters. Both Polhena and Mirissa recorded a mean pH of 8.2, while Unawatuna had a slightly lower mean pH of 8.1. Coastal pH typically ranges from 7.5 to 8.5, according to most studies (Hinga, 2002). Even minor fluctuations in pH can significantly affect the solubility and toxicity of various compounds, ultimately impacting ecosystem health (Hinga, 2002; Jayawardena et al., 2024). In certain instances, the upwelling of nutrient-rich, corrosive waters may also influence coastal pH levels (Carstensen & Duarte, 2019). The pH values did not vary significantly compared to previous research (Manage et al., 2022; Manikarachchi et al., 2014).

All three beaches recorded a mean electrical conductivity (EC) of 57.0 mS cm-1. Similarly, the mean salinity across the beaches was 36.2 ppt, aligning with studies indicating that coastal salinity should exceed 25 ppt (Hinga, 2002). TDS values were also consistent, with an average of 28.0 across all locations. DO levels were above 4 mg/L at all three beaches, suggesting good water mixing. Typically, DO concentrations are higher near the water's surface due to oxygen diffusion from the atmosphere (Jayawardena et al., 2024). However, coastal eutrophication can reduce DO levels, altering water chemistry, particularly pH (Lee et al., 2023). Manikarachchi et al., (2014) reported a comparatively lower DO value of 7.1 mg/L at Polhena, while this study recorded 7.7 mg/L. In contrast, Manage et al. (2022) reported DO values greater than 8 mg/L for Unawatuna and Mirissa. The DO values can vary depending on the time of sampling, water mixing, and wind effects (Dawson et al., 2023).

Sri Lanka does not yet have established coastal water standards; therefore, the results were compared with the ASEAN water quality Criteria (AMWQC), and the Marine water quality standards of Thailand and Indonesia (Table 3) (AusAID, 2008). According to the standards, the minimum acceptable DO concentration is 4 mg/L, and all sampled locations exceeded this threshold.

Nitrogen (N) and phosphorus (P) are essential macronutrients in seawater that play a vital role in supporting primary productivity (Siriwardana et al., 2024a). While these macronutrients are crucial for the growth of marine organisms, excessive anthropogenic inputs such as terrestrial sewage discharges, aquaculture effluent, and fertilizer-laden runoff can lead to nutrient over-enrichment. This process can degrade water quality and render coastal water unsuitable for human use (Siriwardana et al., 2024b).

Among the study sites, PO_4^{3-} concentrations were slightly higher at Unawatuna (0.0263 mg/L) compared to Mirissa (0.0190 mg/L) and Polhena (0.0204 mg/L). Unawatuna also exhibited elevated levels of NO_2^- compared to the other two beaches. In contrast, Polhena recorded the highest mean NO_3^- concentration among the 3 locations, indicating localized nutrient input dynamics that may vary. Regarding PO_4^{3-}, all the selected standards (AusAID, 2008) define a maximum

Table 2 The descriptive statistics (maximum, minimum, mean and standard deviation) of selected 13 parameters for Unawatuna, Mirissa and Polhena

	Unawatuna			Mirissa			Polhena		
	max	min	mean ± std	max	min	mean ± std	max	min	mean ± std
pH	8.4	7.9	8.1±0.1	8.4	7.9	8.2±0.1	8.5	7.9	8.2±0.2
EC (mS/cm)	58.6	55.8	57.1±0.6	59.0	54.6	57.1±0.7	58.1	55.8	57.0±0.6
Salinity (ppt)	37.6	34.3	36.2±0.8	37.8	34.7	36.2±0.8	37.7	34.4	36.2±0.8
TDS (mg/L)	28.8	27.4	28.0±0.3	29.0	26.8	28.0±0.3	28.6	27.4	28.0±0.3
WT (°C)	31.2	27.5	28.9±1.2	31.6	27.4	28.8±1.1	30.6	27.2	28.7±1.0
DO (mg/L)	8.6	6.8	7.8±0.4	8.6	7.2	7.9±0.4	8.3	6.8	7.7±0.4
Turbidity (NTU)	6.7	0.9	3.3±1.5	6.7	0.6	3.5±1.5	10.2	0.9	3.7±1.7
Phosphate (mg/L)	0.1286	0.0098	0.0263±0.0207	0.0565	0.0068	0.0190±0.0145	0.0996	0.0087	0.0204±0.0157
Nitrate (mg/L)	0.0717	0.0002	0.0167±0.0129	0.0326	0.0005	0.0161±0.0062	0.1446	0.0005	0.0186±0.0216
Nitrite (mg/L)	0.0660	0.0017	0.0112±0.0089	0.0210	0.0004	0.0074±0.0038	0.0217	0.0034	0.0095±0.0048
TSS (mg/L)	54.4	11.5	26.3±9.6	45.2	11.6	23.8±7.8	66.8	12.0	29.1±11.2

Table 3 The comparison of the results obtained by previous research carried out for the same locations and the ASEAN Marine Water Quality Criteria, the Marine water standards for Thailand and Indonesia

Parameter	Unawatuna (This study)	Mirissa (This study)	Polhena (This study)	Unawatuna (Manage et al., 2022)	Mirissa (Manage et al., 2022)	Polhena (Manikarachchi et al., 2014)	ASEAN (AusAID, 2008)	Thailand (AusAID, 2008)	Indonesia (AusAID, 2008)
pH	8.1±0.1	8.2±0.1	8.2±0.2	8.6±1.2	8.5±0.7	8.5±0.1	[a]	[a]	[a]
EC (mS/cm)	57.1±0.6	57.1±0.7	57.0±0.6	57.5±0.4	51.0±0.8	–	[a]	[a]	[a]
WT (°C)	28.9±1.2	28.8±1.1	28.7±1.0	26.5±0.2	25.6±0.3	28.5±0.6	[a]	[a]	[a]
DO (mg/L)	7.8±0.4	7.9±0.4	7.7±0.4	8.2±3.4	8.3±2.5	7.1±0.9	4.00	4.00	>5.00
Turbidity (NTU)	3.3±1.5	3.5±1.5	3.7±1.7	[a]	[a]	[a]	[a]	[a]	[a]
Phosphate (mg/L)	0.026±0.021	0.019±0.015	0.020±0.016	0.117±0.008	0.130±0.003	0.110±0.100	0.015	0.015	0.015
Nitrate (mg/L)	0.017±0.013	0.016±0.006	0.019±0.022	<0.01	<0.01	[a]	0.06	0.02	0.008
Nitrite (mg/L)	0.011±0.009	0.007±0.004	0.010±0.005	<0.001	<0.001	0.050±0.010	0.055	[a]	[a]

Remark: [a] value not defined.

acceptable concentration of 0.015 mg/L; nonetheless, the PO_4^{3-} concentrations in all beaches exceeded this limit, both in this study and in previous ones. This could be due to the sewage discharge, grey water discharge by nearby hotels and restaurants and urban runoff. For NO_3^- and NO_2^-, the selected coastal areas had lower concentrations compared to the specified limits in most standards, except for the Indonesian standards, which define a minimum acceptable NO_3^- level of 0.008 mg/L (AusAID, 2008).

2. Spatial and temporal patterns

The Shapiro-Wilk test revealed that the data were not normally distributed for most of the water quality parameters and proceeded with the PERMANOVA test.

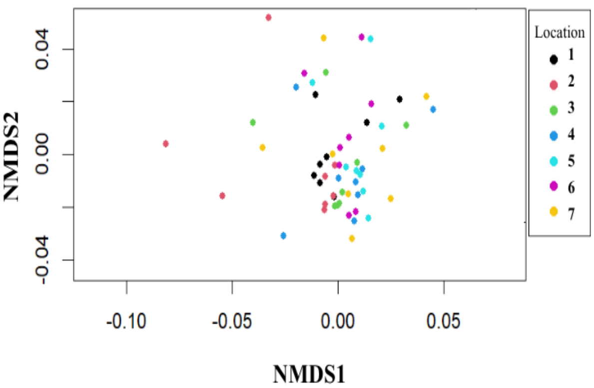
2.1 Unawatuna

The PREMANOVA test indicated no significant spatial variation ($R^2 = 0.00166$, $F = 0.0899$, $p = 0.711$) of water quality between the sampling locations in Unawatuna. But the water quality has shown a significant difference ($R^2 = 0.52943$, $F = 7.7148$, $p = 0.001$) between months, specifically for TSS, TDS and turbidity.

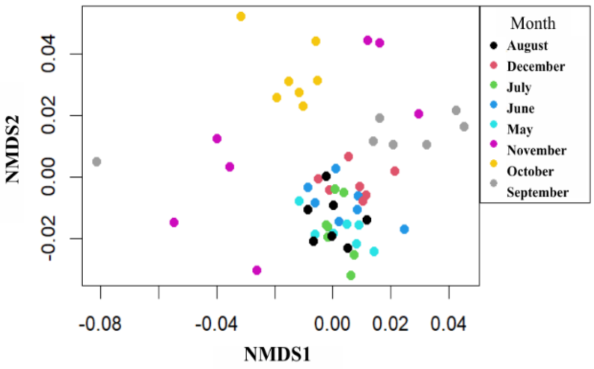
The NMDS plot (Fig. 2a, left) shows that the majority of sampling locations overlap, indicating similar water quality with only minor variations. This plot supports the PERMANOVA results, which found no statistically significant difference in water quality among locations ($p>0.05$). In Fig. 2b (right), the points overlap except for September, October and November. This clearly shows the impact of the monsoon on water quality. The water quality remained similar during the southwest monsoon (May-August) but deviated during the intermonsoon period.

2.2 Mirissa

Mirissa had no spatial variation ($R^2 = 0.00439$, $F = 0.2027$, $p = 0.636$) between locations and no temporal variation ($R^2 = 0.2042$, $F = 1.4663$, $p = 0.203$)



(a)



(b)

Fig. 2 NMDS ordination of water quality at Unawatuna. (a) Spatial clustering of sampling locations. (b) Temporal separation by month. Each point represents one sample; ellipses indicate similarities in water quality profiles.

between months. Similar to Unawatuna, water quality had only a minor variation between locations, but deviated largely in September, October and November (Fig. 3). indicating the influence of the south-west monsoon and intermonsoon on water quality.

2.3 Polhena

Polhena showed a significant spatial variation ($R^2 = 0.14566$, $F = 7.8424$, $p = 0.004$), specifically with DO and no significant temporal variation between months ($R^2 = 0.19946$, $F = 1.4238$, $p = 0.209$). Aligned with the observations made in Unawatuna and Mirissa, the water quality in September, October and November deviated from the water quality of other months (Fig. 4).

It can be suggested that the water quality in Unawatuna and Mirissa was generally consistent among sampling locations due to insignificant spatial variation. This is mostly due to the proper mixing and dispersion of pollutants. In contrast, Polhena had a significant spatial variation among locations, mainly due to DO.

Temporal analysis revealed that Unawatuna had significant variation between months, driven by TSS, TDS, and turbidity, emphasizing the impact of monsoonal runoff. Although PERMANOVA did not observe any significant temporal variation in Mirissa or Polhena, NMDS plots revealed separate clustering of September, October, and November samples at all beaches, reflecting the influence of the south-West monsoon and intermonsoon on coastal water quality in all three beaches.

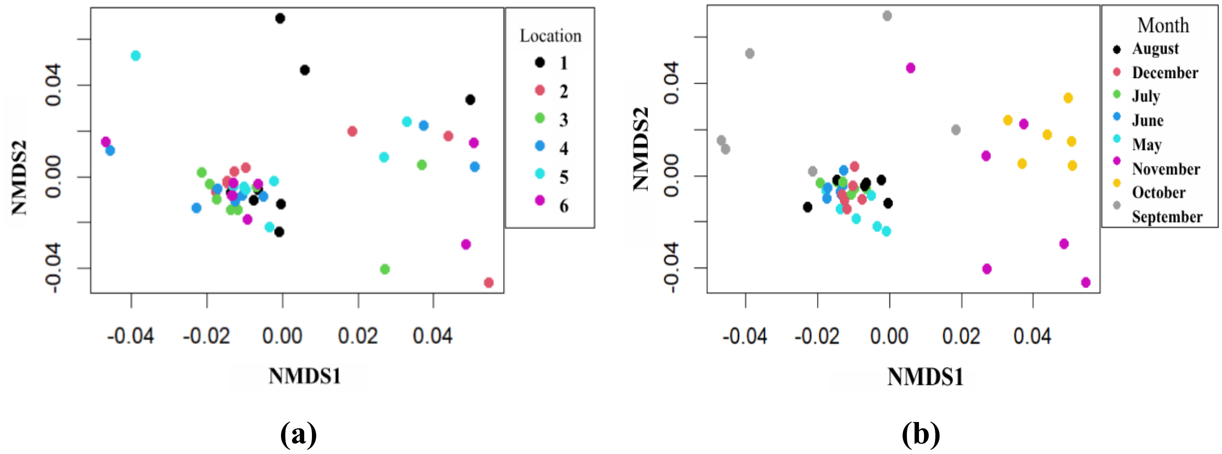


Fig. 3 NMDS ordination of water quality at Mirissa. (a) Spatial clustering of sampling locations. (b) Temporal separation by month. Each point represents one sample; ellipses indicate similarities in water quality profiles.

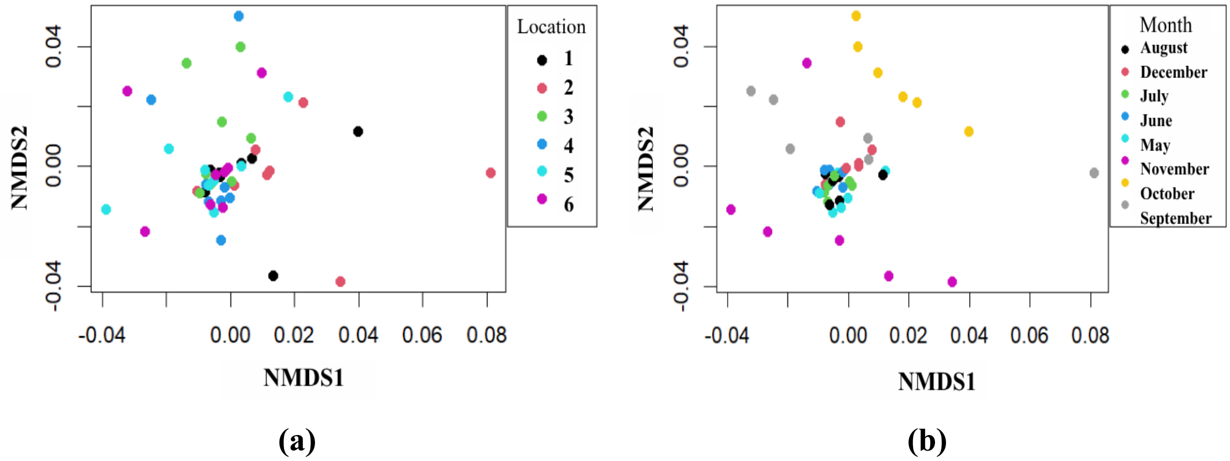


Fig. 4 NMDS ordination of water quality at Polhena. (a) Spatial clustering of sampling locations. (b) Temporal separation by month. Each point represents one sample; ellipses indicate similarities in water quality profiles.

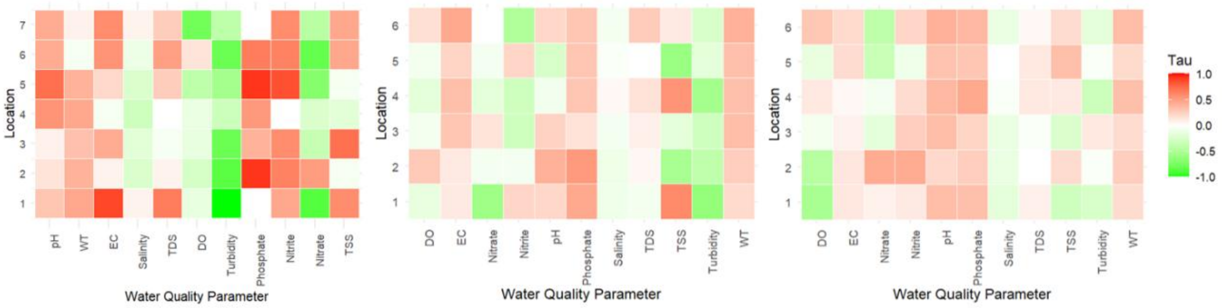


Fig. 5 Heat maps showing temporal trends (May–December 2023) in key water quality parameters across three beaches. (a) Unawatuna, (b) Mirissa, and (c) Polhena. Warmer colors indicate increasing values; cooler colors indicate declining values.

3. Trend analysis

When analyzing the trends in water quality from May to December at each beach, both positive and negative trends were observed across parameters (Fig. 5). However, none of these trends were statistically significant ($p>0.05$) for any parameter at any of the beaches. In Unawatuna, PO_4^{3-} and NO_2^- levels showed increasing trends, while NO_3^- generally exhibited a decreasing trend, except at location 2. Particularly, location 2 can be identified as more polluted, likely due to the discharge from a canal that brings runoff from the nearby village into the beach. Mirissa and Polhena also showed increasing trends in PO_4^{3-}, though these trends were weaker compared to Unawatuna, as reflected in the Tau values. Turbidity displayed a declining or stable trend at all three beaches. The stronger nutrient increases observed in Unawatuna could be attributed to higher levels of anthropogenic activities compared to the other beaches.

4. Coastal water quality index (CWQI)

An overall understanding of water quality cannot be obtained by analyzing individual parameters in isolation. To assess the general condition of water, a water quality index (WQI) can be utilized, which integrates multiple parameters into a single representative value. In the WAI method, each water quality parameter is assigned to a weight based on its relative importance. In this study, pH, DO, turbidity, PO_4^{3-}, NO_3^-, and NO_2^- were selected for the development of the index, and each was considered equally important when assigning weights.

Table 4 Grades of coastal water quality index (CWQI) and status of water quality rating (Gonul et al., 2023)

WQI	Category of water quality
<50	Excellent
50–100	Good
100–200	Poor
200–300	Very Poor
>300	Unsuitable

The WQI scale defined by Gonul et al. (2023) was used to categorize the WQI values (Table 4). The WQI values in Unawatuna ranged from 14 (excellent) to 118 (poor). Location 2 recorded values of 109 (poor) in September and 118 (poor) in October. This finding correlates with the statistical analysis, highlighting the influence of the canal outlet on the beach's water quality. The Mann-Kendall test showed positive tau values for locations 1 to 6, indicating an increasing trend in WQI over time. This suggests a decline in water quality at these locations. In contrast, location 7 showed a negative tau value, indicating an improvement in water quality over time. Nevertheless, the trend was not significant ($p>0.05$) (Fig. 6a and Fig. 6b).

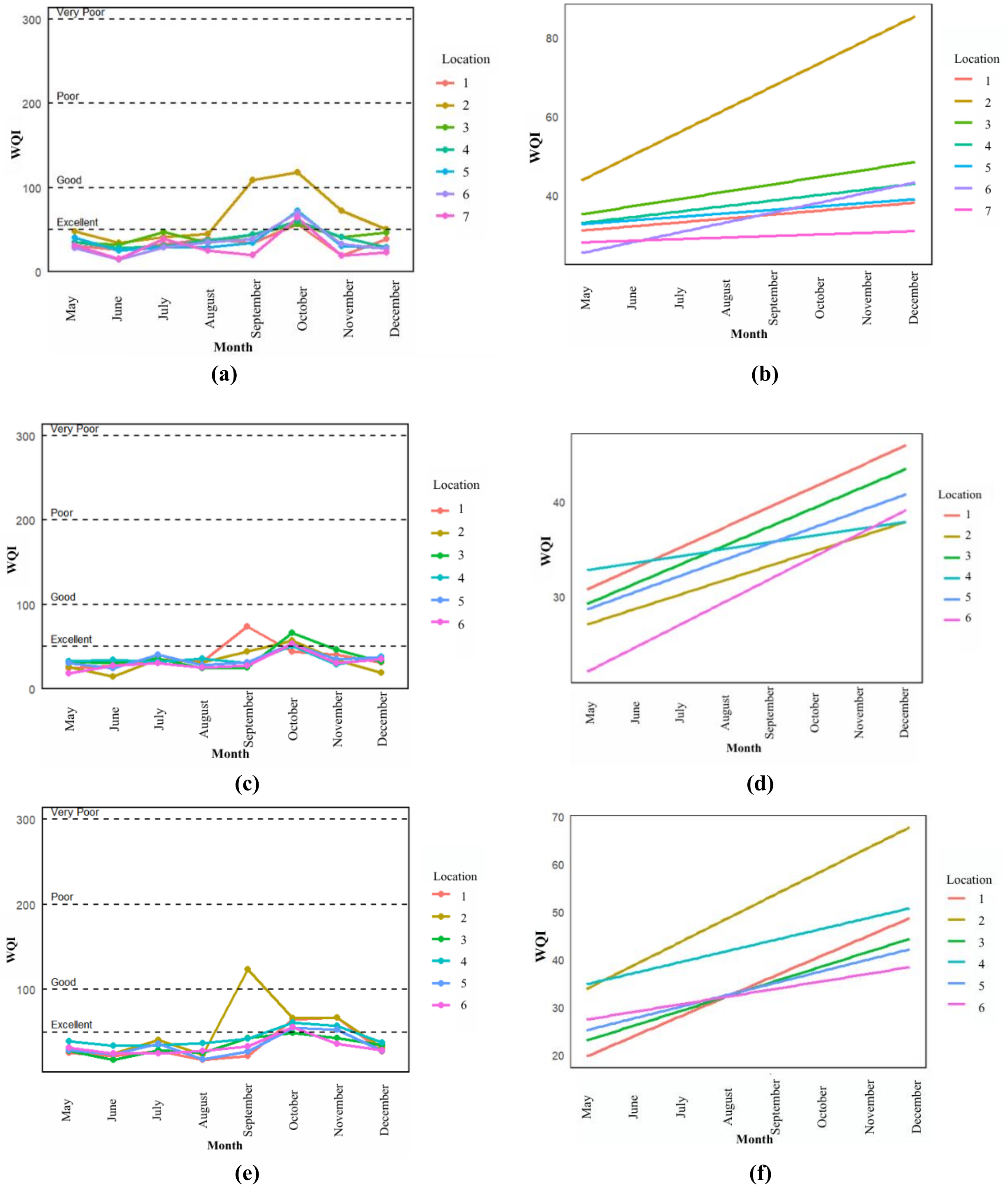


Fig. 6 Variation and trends of Coastal Water Quality Index (CWQI) from May to December 2023. (a) Monthly CWQI values at Unawatuna by location. (b) Temporal trends in CWQI at Unawatuna. (c) Monthly CWQI values at Mirissa. (d) Temporal trends in CWQI at Mirissa. (e) Monthly CWQI values at Polhena. (f) Temporal trends in CWQI at Polhena. Thresholds for "Excellent," "Good," and "Poor" water quality are indicated.

WQI values in Mirissa ranged from 14 (excellent) to 74 (good). Location 1 recorded the highest WQI in September. All locations exhibited a non-significant ($p>0.05$) upward trend (positive tau), indicating a gradual deterioration of water quality over time (Fig. 6c and Fig. 6d).

In Polhena, WQI values ranged from 17 (excellent) to 124 (poor), with the highest value also observed in September, similar to Mirissa. Likewise, all locations in Polhena showed a non-significant ($p>0.05$) upward trend (positive tau), suggesting a similar pattern of water quality decline over time (Fig. 6e and Fig. 6f).

5. National legal framework for marine and recreational water protection

Sri Lanka's core laws for water protection include the National Environmental Act (1980), the Marine Pollution Prevention Act (1981), and the Coast Conservation and Coastal Resource Management Act (2011), supported by fisheries and aquaculture legislation (Central Environmental Authority, 1980; Fauna and Flora Protection Ordinance, 1937; National Aquaculture Development Authority of Sri Lanka Act, 1998). These laws provide a strong foundation for pollution control and resource management. However, the CWQI findings of this study show moderate to poor water quality at Unawatuna, Mirissa, and Polhena, which suggests poor implementation and enforcement, especially in controlling nutrient and organic matter inputs associated with tourism and coastal activities.

6. International legal instruments for marine protection

Several international conventions and protocols provide a framework for managing marine pollution and safeguarding recreational waters (Nauke & Holland, 1992). The London Convention (1972) and its 1996 Protocol regulate dumping at sea (Hong & Lee, 2015; Nauke & Holland, 1992), while MARPOL (1973/78/97) addresses vessel-based pollution from oil, sewage, and chemicals (Griffin, 1994). To strengthen emergency response, the OPRC (1990) and its HNS Protocol (2000) promote coordinated action during spills (Parker et al., 2014). The Ballast Water Management Convention (2004) prevents invasive species transfer (Olenin et al., 2016), and other agreements such as the Anti-Fouling Systems Convention (2001), Basel Convention (1989), and Nairobi Convention (2007) contribute to broader marine protection (Ahmed, 2020).

Such instruments primarily address sea-based pollution; however, the CWQI results from the current study showed that land-based nutrient enrichment and organic matter inputs were the predominant causes of moderate to poor water quality in Unawatuna, Mirissa, and Polhena beaches. This gap highlights the need to complement international maritime agreements with stronger local controls on land-based discharges.

7. Global and regional guidelines for water quality monitoring

Sri Lanka lacks national coastal water quality standards; therefore, the current study has used ASEAN criteria as thresholds (AusAID, 2008). Broader frameworks, such as the EU Water Framework Directive (Chave, 2007) and the WHO guidelines for recreational water (World Health Organization, 2003; 2021), highlight risk-based monitoring and public health protection. Such broader models are crucial to Sri Lanka, as the seasonal declines in DO and nutrient increases observed in the current study pose risks for recreational use of beaches such as Mirissa and Unawatuna.

8. Institutional arrangements and stakeholder roles

Numerous agencies share responsibility for institutional arrangements and stakeholder roles, such as the Coast Conservation and Coastal Resource Management Department (CC & RMD), the Central Environmental Authority (CEA), and the Marine Environment Protection Authority (MEPA), with scientific input from the National Aquatic Resources Research and Development Agency (NARA) (Coast Conservation & Coastal Resource Management Department, 2025). Despite this coverage, the coordination and enforcement of such institutes in the local context are limited. The nutrient enrichment and DO reductions reported during several months of sampling indicate that institutional mechanisms are not yet effective in maintaining recreational water quality.

9. Challenges and future directions

Sri Lanka should establish national coastal water quality standards, expand spatiotemporal monitoring to capture seasonal and local variation, and improve inter-agency coordination and enforcement, particularly in tourism-intensive beaches, to address these gaps. By linking legal, institutional, and international frameworks with CWQI results, these steps would move Sri Lanka closer to sustainable management of its coastal waters.

Conclusion

This study presents a first-of-its-kind, comprehensive spatiotemporal assessment of coastal water quality across three ecologically and economically significant beaches, Unawatuna, Mirissa and Polhena in southern Sri Lanka, thereby offering crucial baseline data to inform evidence-based coastal management and policy development. This study aimed to (i) assess the spatiotemporal variation of water quality, (ii) evaluate overall water quality status using the CWQI, and (iii) provide relevant management insights for Sri Lanka's southern beaches. Across the three sites, most in-situ parameters were within recommended limits. Nevertheless, PO_4^{3-} concentrations frequently exceeded ASEAN thresholds (0.015 mg/L), with values reaching up to 0.026 mg/L, indicating anthropogenic nutrient enrichment. Spatial variability was evident in Polhena, influenced by DO levels, with seasonal effects observed in October and November. The CWQI ranged from 14 (excellent) to 124 (poor), showing a declining trend of water quality in these beaches. These results confirm the influence of monsoonal seasonality and site-specific pressures, thereby fulfilling the study's objectives. The findings highlight the need for proactive, data-driven coastal management. Establishing national coastal water quality standards aligned with ASEAN and MARPOL benchmarks, coupled with risk-based and site-specific monitoring, is essential to safeguard recreational beaches. Future research should integrate microbial and biological parameters, extend monitoring beyond one year to capture interannual variation, and link water quality to land-based pollution sources. Such steps will strengthen evidence-based policy and ensure sustainable management of Sri Lanka's coastal ecosystems.

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