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Water quality within the greater Suva urban marine environment through spatial analysis of nutrients and water properties

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ABSTRACT

Coastal ecosystems in Pacific Island Countries and Territories are vital to local livelihoods, yet increasingly face pressures from urbanization. In Fiji, the Greater Suva Urban Area, where one-third of the nation's population live, exemplifies these challenges. This study examines spatial and temporal water quality variations in the coastal zone, focusing on physicochemical, nutrients, and clarity parameters. Using a Seabird Scientific SBE19 CTD and Thermo Scientific Orion™ AQUAfast™ colorimeter, coupled with hierarchical clustering and principal component analysis, six water quality clusters were identified, influenced by oceanic processes, river inputs, and anthropogenic activities. Key findings highlight nutrient enrichment near urban centers particularly at the Kinoya Sewage Treatment Plant outfall, where ammonia exceeded 17.8 mg/L, and significant variation observed in nitrate (up to 0.24 ± 0.06 mg/L) and nitrite (up to 0.24 ± 0.06 mg/L) concentrations near river mouths. Seasonal runoff contributed to elevated turbidity (up to 3.5 NTU) and total suspended solids (up to 14.7 mg/L) levels during wet months. Salinity, and temperature exhibited strong spatial and seasonal variability, reflecting land-ocean interactions and restricted water exchange. These findings emphasize the need for targeted action to mitigate nutrient pollution, urban runoff, and wastewater impacts. This study provides a cost-effective monitoring framework for water quality management, offering insights for sustainable coastal resource management in Fiji and other Pacific regions amidst urbanization and climate change.

1. Introduction

Coastal marine environments, located at the interface between land and sea and, play a crucial role in ecological, economic, and societal systems (Häyhä and Franzese, 2014; Winder et al., 2017). These areas, particularly lagoons and bays, undergo a continuous exchange of materials and energy from land-based drainage and runoff, coupled with oceanic processes and flushing (Netto and Fonseca, 2017; Yang et al., 2013). Anthropogenic pressures; mainly urbanization, pollution, and ocean creep, further complicate coastal water dynamics, degrading water quality through processes such as eutrophication, increased sedimentation, and biological and chemical contamination (Carpenter et al., 2008; Yang et al., 2013). These intricate interactions create a complex range of water bodies with varying nutrient and sediment levels, as well as fluctuations in parameters such as salinity, dissolved oxygen, and temperature (Bierman et al., 2009; Xiong et al., 2022; Yuan et al., 2023). The dynamics and contributions of these factors can be quantified through indices of water quality (Gupta et al., 2003; Haggarty et al., 2012; Nguyen and Sevando, 2019; Yang et al., 2013).

The United Nations Sustainable Development Goals (UN-SDGs) 14 aims to conserve and sustainably use the oceans, seas and marine resources for sustainable development, urging signatories to monitor and improve water quality in coastal environments by reducing pollution and impurities (Diz et al., 2017; Roser, 2023; UNSD, 2022). To achieve this, various countries have implemented protocols to monitor water parameters to determine surface water quality based on set standards (Drasovean and Murariu, 2021; Gholizadeh et al., 2016; Gupta et al., 2003; Wu et al., 2020). While various parameters – including nutrients, biomass, heavy metals concentrations, coral cover, and microplastics concentrations – can be used to determine water quality within aquatic

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ecosystems, their limits and variability often differ between countries or applications (Drasovean and Murariu, 2021; Gupta et al., 2003). The identification of these parameters and development of the water quality standards are typically obtained based on rigorous spatial and temporal studies of water parameters (Drasovean and Murariu, 2021; Medina-Gómez and Herrera-Silveira, 2003; Zhou et al., 2006).

Monitoring the physicochemical properties and nutrient levels of coastal water bodies is crucial for their classification and management globally (Balasubramanian et al., 2024; Chávez-Díaz et al., 2019). Nutrient concentrations; including ammonia, nitrate, and phosphate, are essential for identifying potential eutrophication risks and managing human impacts (Revilla et al., 2009; Achtak et al., 2024). Additionally, physicochemical parameters like salinity, temperature, transparency, and oxygenation levels, provide insights into overall water quality, supporting sustainable management practices (Achtak et al., 2024; Karamfilov et al., 2019; Olsen et al., 2014). Continuous monitoring, informed by advanced data analysis methods like Principal Component Analysis (Mahapatra et al., 2012; Praveena and Aris, 2012), is essential for understanding both natural and anthropogenic influences, ensuring the protection of coastal ecosystems worldwide.

In Pacific Island Countries and Territories (PICTs), the importance of coastal systems on livelihoods is amplified, due in part to traditional significance, but also because 95 % of people live within five kilometers of coastal zones and rely directly or indirectly on coastal resources for survival (Andrew et al., 2019). Despite the many benefits these ecosystems provide to PICT communities, they often face persistent acute stress from land-based runoff (André et al., 2021; Dehm et al., 2020, 2021; Naidu et al., 1991; Suratissa and Rathnayake, 2017; Varea et al., 2020). Furthermore, a poor understanding of water quality due to underregulated urbanization, development and industrial activity, as well as a lack of coastal management policies, has exacerbated the issue ((National Integrated Water Resource Management Diagnostic Report - Fiji Islands, 2007); Sanderson et al., 2022; Varea et al., 2020).

Fiji, as a resource-dependent state, grapples with competing demands for land use in agriculture, tourism, transport, urbanization, modern infrastructure, and other sectors that affect the health and quality of surrounding water bodies (Farran, 2020; Singh et al., 2009). While water quality standards in Fiji, as defined in the Environment Management Regulations 2007 (Fijian Government, 2007), pertain only to effluent discharge into the environment, urbanization has led to wastewater contamination in estuaries and marine recreational waters, necessitating specific guidelines for their management (Kumar, 2010; Lal et al., 2021). However, there is currently a lack of long-term national monitoring plans in place for coastal marine systems (Lal et al., 2021). Monitoring efforts to measure contaminants, pollutants or water quality in Fiji's marine areas are generally driven by academic research or sporadic project-based surveys, lacking consistency and comparability with previous studies in terms of methodology and variables; for example, refer to Koliyavu et al., 2021; Morrison et al., 2001; Naidu et al., 1991; Naidu and Morrison, 1994; Pratap et al., 2020 and Singh et al., 2009.

The Greater Suva Urban Area (GSUA) exemplifies the most urbanized and developed metropolitan within the PICTs, experiencing rapid expansion with an urbanization rate of ~57 % in recent years (Sanderson et al., 2022; World Bank Open Data, *2021*). This growth can be attributed mainly to increasing migration into the city as individuals seek economic, educational, healthcare, and recreational opportunities (Sanderson et al., 2022). The GSUA comprises four townships, including Suva City and the towns of Lami, Nasinu and Nausori (Shiiba et al., 2023). Each municipality is overseen by its respective administration, following town plans that were developed many decades ago (e.g., the Suva City plan was developed in 1979) (Phillips and Keen, 2016; Sanderson et al., 2022). These plans are generally outdated and do not adequately account for the complexities and requirements of contemporary urbanization (Asian Development Bank, 2016; Sanderson et al., 2022). Despite the lack of updated vision or objectives for urban development at a city scale, the GSUA has experienced considerable growth, now accommodating a third of Fiji's population (approximately 300,000 residents, see https: //www.statsfiji.gov.fj/). This population increase has placed mounting pressure on the marine environment around the GSUA, both directly through heightened utilization of marine resources and indirectly due to underdeveloped infrastructure and increased waste generation (Dehm et al., 2024). These pressures are expected to intensify, particularly on the periphery of Fiji's urban centers, as population size and development continue to rise.

To begin to protect coastal marine environmental health around PICTs, it is crucial to develop a cost-effective and simple water quality monitoring strategy (Liu et al., 2018; Naidu et al., 1991; Naidu and Morrison, 1994; Varea et al., 2020). However, achieving this requires a thorough understanding of the spatial and temporal patterns of the physical and biochemical processes involved (Medina-Gómez and Herrera-Silveira, 2003; Schuwirth, 2020; Zhou et al., 2006). This study serves as the initial phase of a broader investigation into the correlation between the distribution of coral reef assemblages and variability in water quality and hydrodynamics within the coastal marine environment adjacent to the GSUA. Previous research has focused on a relatively small area within the coastal marine environment near the GSUA, particularly in Laucala Bay (Lal et al., 2021; Morrison et al., 2001; Naidu et al., 1991; Naidu and Morrison, 1994; Pratap et al., 2020; Singh and Aung, 2008). These studies suggest that Laucala Bay's water quality is primarily influenced by sediment, particulate nutrients, and salinity and temperature gradients (Koliyavu et al., 2021; Singh, 2007; Singh et al., 2009). However, their scope was limited to estimating constituent loads within Laucala Bay without exploring the associations between variables that define water quality characteristics. Building on these initial studies, this study aims to characterize water bodies based on their water quality within the coastal area adjacent to the GSUA, by analyzing physicochemical parameters (temperature, salinity, and dissolved oxygen), nutrient levels (nitrate, nitrite, ammonia, and dissolved inorganic phosphate, DIP), water clarity (turbidity and total suspended solids, TSS), and chemical oxygen demand (COD). The objective is to evaluate the environmental health of this region, providing baseline data to inform future monitoring and conservation efforts. The study's findings reveal significant variations in water quality, highlighting areas of concern and offering insights into the potential drivers of environmental change.

To promote replicability and ensure widespread application within the GSUA, Fiji and the broader Pacific region, this study adopts a recent approach utilizing a portable multiparameter colorimeter, such as those described by Ji et al. (2022), Panigrahi et al. (2024) and Thakur and Devi (2022). This cost-effective and Environmental Protection Agency (EPA) approved instrument enables the efficient measurement of nutrients in water samples (Thermo Scientific Orion AQ3700 AQUAfast Colorimeter - Spectroscopy, Spectrophotometry, 2023). The use of multivariate approaches, including hierarchical clustering and principal component analysis (PCA), further strengthens this study's methodology, as they offer a comprehensive understanding of complex data matrices and identify influential factors and sources impacting water systems (Karangoda and Nanayakkara, 2023; Liu et al., 2018; Medina-Gómez and Herrera-Silveira, 2003; Zhou et al., 2006). Through hierarchical clustering, the grouping of similar objects allows for the identification of clusters with shared characteristics (Medina-Gómez and Herrera-Silveira, 2003; Zhou et al., 2006). Simultaneously, PCA simplifies the data by highlighting the key variables influencing water quality variations (Zhou et al., 2006). These techniques contribute to a thorough assessment of the ecological status of the studied systems and provide valuable tools for effective water resource management, while promoting solutions to pollution issues. The ease of adoption and replicability without the need for intricate a priori standards make these methods particularly advantageous. By combining these multivariate statistical analyses, valuable insights into the spatial and temporal variations of water quality along the GSUA can be gained thus facilitating informed decision-making and sustainable coastal resource management in the region.

2. Methods

2.1. Study area and sampling period

The study site is located on the southeastern coast of Viti Levu, Fiji (Fig. 1), focusing on the coastal marine environment of the GSUA. The coastal environment of the GSUA is rich in diverse ecosystems, including fringing and barrier reefs, mangroves, tidal flats, and lagoons (Dehm et al., 2024). The region encompasses several interconnected water bodies, each influenced by varying degrees of human activity and freshwater runoff. Key river systems, including the Rewa River and its distributaries, play a significant role in shaping the coastal environment (Rodda, 2005). The freshwater runoff from these rivers transports pollutants from domestic, agricultural, and industrial sources into the marine ecosystem, further compromising water quality (Rodda, 2005; Tamata et al., 2010). Additionally, wastewater discharge and urban runoff exert significant anthropogenic pressures directly on coastal waters (Morrison et al., 2005; Veitayaki, 2010).

Water properties and circulation patterns are further influenced by the combined effects of the southeast trade winds and the South Pacific Convergence Zone (SPCZ), which create distinct seasonal variability (Rao, 2005; Smith et al., 1994). These climatic factors result in a warm-wet season (November to April) and a cool-dry season (May to October), impacting the region's coastal environment. During the warm-wet season, increased rainfall and river runoff influence water quality, while the cool-dry season brings calmer conditions, with reduced rainfall and less freshwater input, allowing for different marine dynamics to prevail (Singh and Aung, 2009). These seasonal shifts play a crucial role in shaping the water properties and circulation within the GSUA's coastal waters.

Water samples were collected from approximately twenty-five kilometers from either side of the Suva Peninsula, i.e., centered at approximately −18.169° S and 178.438° E with the furthest eastern point being within the Nasilai Bay (∼ − 18.0653° S, 178.6805° E) and the furthest western point being near Naqara in the west (−18.1981° S, 178.2713° E). Sample sites were spaced such that nearshore, mid-lagoon, and fore and aft reef dynamics were captured. In total, 97 sampling stations were assessed, with water samples being collected, and an SBE19 CTD (Seabird Scientific, Washington, USA) deployed at all sites. In total 6 sampling events spread over 12 months took place, with 3 sampling events taking place in the wet season (March, November, January) and 3 in the dry season (June, August, October).

2.2. Nutrient measurements

Nutrient measurements were done using a Thermo Scientific Orion™ AQUAfast™ colorimeter (AQ3700) to determine the concentrations of ammonia (NH_3), nitrate (NO_3^-), nitrite (NO_2^-), DIP, and COD. Water samples were collected from each sampling site using a 4.5 L high density polyethylene (HDPE) sampling bottle from approximately 1 m depth and kept on ice until nutrient measurements were performed, typically within 3 to 5 h following sampling. The measurements of individual nutrients were conducted using assays and reagent formulations based on internationally recognized methods, such as the Deutsche Einheitsverfahren zur Wasser-, Abwasser- und Schlammuntersuchung and the Standard Methods for the Examination of Water and Wastewater (18th Edition, 1992), as well as Photometrische Analysenverfahren (Schwedt, 1989). The measurement procedures are described in the Orion™ AQUAfast™ AQ3700 Portable Colorimeter User Manual from 2017.

2.3. Temperature, salinity, dissolved oxygen and turbidity

In addition to nutrient measurements, other physiochemical water properties were assessed. A calibrated SBE19 CTD (Conductivity, Temperature, Depth) instrument from Sea-Bird Scientific (Washington, USA), along with additional dissolved oxygen (SBE 43, Sea-Bird Scientific, Washington, USA) and turbidity (Campbell Scientific, Utah, USA: OBS-3+) sensors were deployed at each station. For stations with depths >100 m, the SBE19 CTD was deployed to approximately 100 m depth. The collected data were extracted from instruments and cleaned using

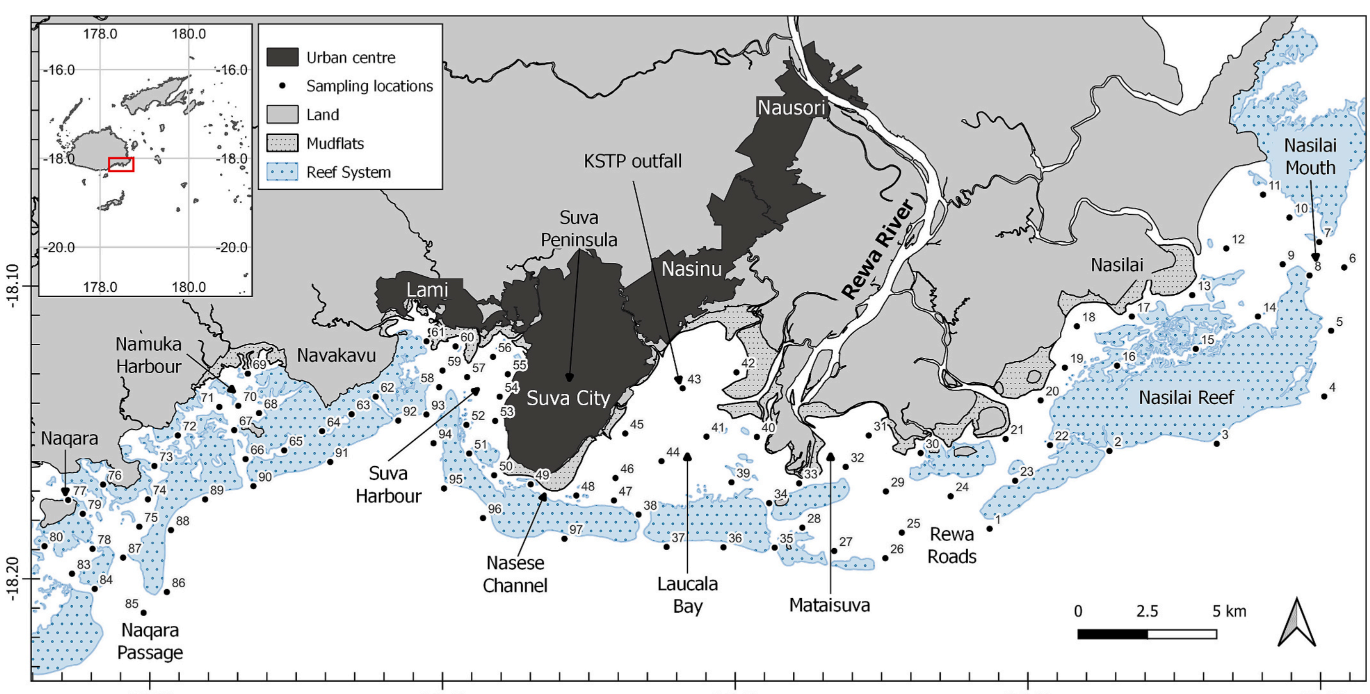

Fig. 1. Map of the study area along the south-eastern coast of Viti Levu, Fiji, showing the locations of 97 numbered sampling sites within the Greater Suva Urban Area (GSUA). Data source: Ministry of Lands & Mineral Resources, Fiji.

the Seasoft V27 software (SBE Data Processing 7.26.8, Sea-Bird Scientific) by applying standard filters to remove spurious readings, including those caused by sensor drift, signal spikes, or outliers.

2.4. Total Suspended Solids (TSS)

The concentration of TSS was determined by filtering between 0.3 L to 1.0 L of water collected at 1 m depth through 0.45 μm Nuclepore™ Whatman® filters with a diameter of 47 mm. The variability in the volume of filtered water depended on the saturation of solids within the sample. Water samples with a higher concentration of suspended solids required a smaller volume of water to be filtered, as the filter would block more quickly, whereas samples with lower suspended solids loads allowed for the filtration of larger volumes before clogging occurred. Before filtration, all filter papers were dried at 60 °C for 24 h and weighed. After filtration, 0.02 L of ammonium formate was filtered over the samples to dissolve any remaining salt crystals. The filter papers were then dried again at 60 °C for 24 h and weighed. The difference in weight between the dry filter paper before and after filtering, relative to the volume filtered, provided the total weight of suspended solids (TSS).

2.5. Data analysis

The observed water parameters were examined to assess spatial variability, intra-annual variations, and differences between wet and dry seasons. Box and whisker plots were used to visualize statistical measures of central tendency and dispersion for each parameter. The relationship between all properties observed was examined through Pearsons's correlation coefficient.

Principal Component Analysis (PCA) was used to identify the key variables with the highest influence on water quality characteristics. The Principal Component Analysis involved the following steps (Liu and You, 2022; Al-Mutairi et al., 2014): To account for the contrasting scales of the different variables, data were first treated by z-transformation and outliers removed. Eigenvalues were generated, and data projected onto the principal components (loading) before the score matrix was obtained. Before conducting the PCA, both the Kaiser Criterion and Scree Plot were used to examine the validity of the PCA. Subsequently, PCA was conducted independently on yearly average data between each data point.

Hierarchical agglomerative cluster analysis is a connectivity-based clustering algorithm available for water quality assessment and used to classify variables into clusters with high similarities within classes and high variance between classes (Kitsiou and Karydis, 2011; Feisal et al., 2023). The following steps were implemented. First, all parameters were z-scale standardized, and outliers removed based on a z-score threshold of ±3, beyond which data points were considered extreme. Following this, the distance between objects was calculated using Euclidean distance. Pairs of objects in proximity (distance) were linked into binary clusters and larger clusters until a hierarchical tree was formed, following Ward's minimum variance hierarchical linkage method (Feisal et al., 2023). Hierarchical agglomerative cluster analysis was conducted independently of the PCA, on yearly averages data.

All data analyses were conducted in R (version 4.2.1), utilizing various open-access packages for statistical analysis and visualization. For data pre-processing, the *dplyr* package (Wickham et al., 2023) was used to manipulate and filter datasets, while *prcomp* from base R was used for conducting the PCA (R Core Team, 2023). To visualize and interpret PCA results, the *factoextra* package (Kassambara and Mundt, 2020) was employed. Hierarchical clustering was performed using the *cluster* package (Maechler et al., 2024). Spatial analysis and depictions were conducted using QGIS version 3.22.10.

2.6. Quality control

Orion™ methods (Thermo Fisher Scientific, Massachusetts, USA) that use EPA-approved test methodology and are acceptable for EPA reporting were employed (Thermo Scientific Orion AQ3700 AQUAfast Colorimeter - Spectroscopy, Spectrophotometry, 2023). To ensure that any delay between collection of water samples and subsequent measurement did not impede nor adversely affect the measurements, a set of 3 water samples were collected and measured directly without delay, and also 2, 4 and 6 h after sampling. No measurable differences in results were observed for all 5 parameters. To prevent discrepancies with regards to TSS, sampling and lab analyses were conducted in triplicate, and filter papers were retained in the oven at 60 °C until required. Furthermore, a rigorous chain of custody protocol was implemented to ensure proper data management and labeling, including keeping filter papers were kept within petri dishes when transported.

3. Results

3.1. Physiochemical water properties across sites

The yearly average temperature across the GSUA coastline sampling area ranged from 26.76 ± 0.99 °C to 28.77 ± 0.77 °C (Fig. 2; panel 1). The lowest average temperature was recorded at the outer reef along Nasilai Reef, while the highest temperature was observed at the Kinoya Sewage Treatment Plant (KSTP) outfall in the Laucala Bay. Temperature gradients showed distinct spatial distributions, i.e. an east-west gradient – with cooler temperatures generally in the east and warmer temperatures in the west (except nearshore sites in Laucala Bay); and a shoreline-open water gradient, with nearshore sites warmer than open-water locations. The warmest zones were nearshore environments (Namuka and Naqara bays, Suva Harbour and Laucala Bay), while cooler temperatures were recorded along the outer reef environment between the Nasilai Mouth and Rewa Roads. Cooler sites exhibited greater temperature fluctuations throughout the year. The highest temperature of the year (29.87 °C) was recorded at the KSTP outfall (site 43) in March, while the lowest temperature (25.52 °C) was recorded in the open ocean along Nasilai reef (site 2) in August. Monthly trends (Supplementary Fig. 1), showed March was the warmest month (28.1 °C to 29.9 °C), followed by January (27.3 °C to 29.3 °C) and November (27.0 °C to 29.0 °C). August was the coldest month (25.5 °C to 28.3 °C), followed by June (26.1 °C to 28.5 °C) and October (26.1 °C to 28.6 °C). Spatially, all months exhibited a similar east-west trend, where eastern sites were generally cooler than western sites, with the exception for March, November, and January, when the warmest location was recorded within Laucala Bay. Across all months, outer reef sites remained cooler than nearshore sites. While March had the highest temperatures overall, no significant difference was noted.

The lowest salinity (26.00 ± 1.46 PSU) was recorded at the Vunidawa distributary mouth in Laucala Bay, while the highest (34.80 ± 0.51 PSU) occurred at site 83 in the Naqara passage (Fig. 2; panel 2). Salinity was lowest near the distributaries of the Rewa River in the Laucala Bay, Mataisuva, and along the Nasilai coastline. Conversely, salinity was higher along the western areas, where major river systems were absent gradually increasing westward from the Laucala Bay. The highest variability in salinity was observed along the Nasilai coast, Rewa Roads, and Laucala Bay. Salinity in Suva Harbour was relatively stable (31 to 32 PSU), increasing to 32–24 PSU from the Namuka coastal area westward, with highest salinity consistently recorded along the outer reef at the western sites. Monthly variations showed the lowest salinity in January, March, and November (24.0 to 34.5, 24.5 to 35.0, and 25.7 to 34.9 PSU, respectively; Supplementary Fig. 2). In June, August, and November, salinity increased (26.6 to 35.5, 27.5 to 35.9, and 27.3 to 35.9 PSU, respectively). However, no noticeable difference was observed in salinity across the months.

Average dissolved oxygen for the year, ranged from 6.40 ± 0.07 mg/L at site 68 in Namuka Harbour to 6.78 ± 0.24 mg/L at site 86 along the outer reef (Fig. 2; panel 3). Dissolved oxygen was generally lowest along reef flats and nearshore environments of the Namuka-Naqara area,

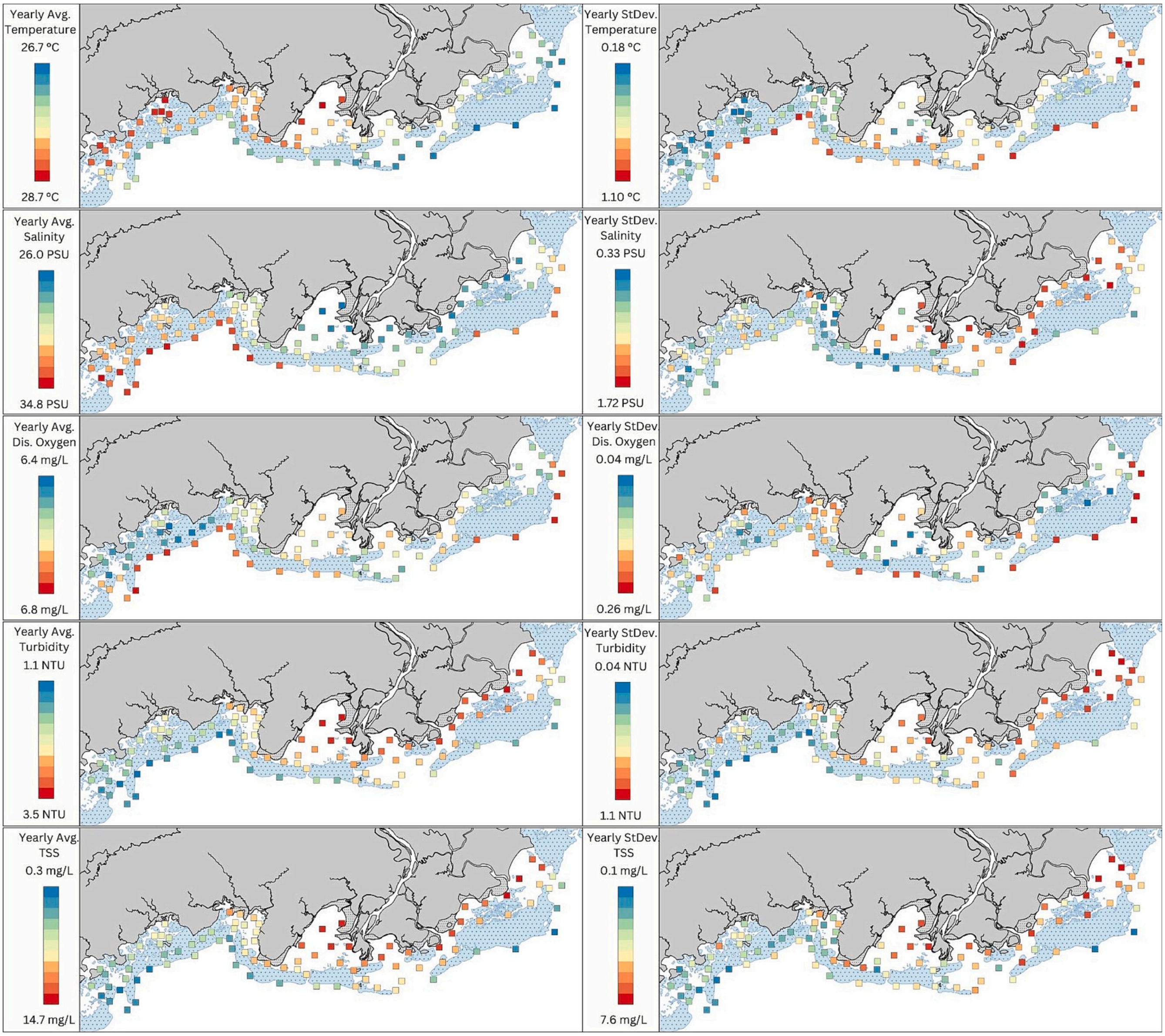

Fig. 2. Spatial distribution of annual averages (left column) and standard deviations (right column) of temperature (panel 1), salinity (panel 2), dissolved oxygen (panel 3), turbidity (panel 4), and total suspended solids (TSS) (panel 5).

coastal waters of Suva Harbour and Nasilai, and within the Laucala Bay – Rewa Roads zone. The highest dissolved oxygen was observed along the outer reef sites, particularly towards the far east and west. Outer reef sites near Laucala Bay exhibited similar levels of dissolved oxygen as within the bay. No distinct spatial trends in the variability of dissolved oxygen were noted. Monthly variations showed more dissolved oxygen variability in March and August compared to June, October, November, and January (Supplementary Fig. 3). Dissolved oxygen ranged from 6.4 to 6.9 mg/L in June, October, November, and January, while in March and August, broader ranges were observed (6.2 to 7.2 mg/L, and 6.3 mg/L to 6.9 mg/L.

Yearly average turbidity ranged from 1.10 ± 0.04 NTU and 3.50 ± 0.69 NTU (Fig. 2; panel 4). Spatially, turbidity was higher in the east, particularly near the distributaries of the Rewa River in the Laucala Bay, Mataisuva, and Nasilai coastal areas. A land-ocean trend was noticeable, with locations closer to the land experiencing higher turbidity levels, however differences were not significant across the GSUA throughout the year. Monthly variations (Supplementary Fig. 4) consistently showed the highest turbidity levels situated along Laucala Bay, Mataisuva, and Nasilai. In August, turbidity ranged as high as 2.9 NTU, while in March it reached 3.5 NTU. In June, turbidity recorded was 3.6 NTU, followed by 4.1 NTU in November. January and October had turbidity levels of 4.4 NTU and 4.8 NTU, respectively.

Average TSS ranged from 0.30 ± 0.15 mg/L to 14.70 ± 3.8 mg/L (Fig. 2; panel 5). Higher TSS levels were observed along the eastern sites, particularly near the distributaries of the Rewa River in the Laucala Bay, Mataisuva, and Nasilai coast, with moderate levels in the Suva Harbour (2.76 mg/L to 8.56 mg/L), and lowest along the Navakavu coast and farther west (0.01 mg/L to 4.77 mg/L). A land-ocean trend was evident, with higher TSS nearer to river mouths. No significant differences were observed across the greater study area. Monthly variations depict lowest TSS during the months of March, June, and August ranging from as low as 0.01 mg/L to 12.8 mg/L, 0.1 mg/L to 12.9 mg/L, and 0.2 mg/L to 13.2 mg/L, respectively (Supplementary Fig. 5). Higher concentrations were recorded in October (0.4–22.2 mg/L), November (0.2–16.1 mg/L), and January (0.4–17.2 mg/L). Spatially, TSS distribution remained consistent, with the lowest levels at western outer reef sites and the highest near Rewa River distributaries in Laucala Bay, Mataisuva, and

Nasilai.

3.2. Nutrient distribution across sites

Yearly average ammonia concentrations ranged from 0.01 ± 0.008 mg/L up to 1.81 ± 1.17 mg/L, with an outlier peak of 17.8 ± 1.8 mg/L recorded at the KSTP outfall in Laucala Bay (Fig. 8; panel 1). Spatially, ammonia exhibited an east-west gradient and a shore-ocean gradient, with lower concentrations towards the west and farther from land. The lowest concentrations were observed at outer-reef sites (0.003 mg/L to 0.1 mg/L), while the highest concentrations were consistently found within the Laucala Bay and Mataisuva areas (0.45 mg/L to 20.1 mg/L). Coastal waters Nasilai showed higher concentrations compared to sites west of the Suva Peninsula. Monthly trends showed no noticeable changes in ammonia concentrations (Supplementary Fig. 6), but the spatial pattern remained consistent with an east-west and coast-ocean gradient. The KSTP outfall in Laucala Bay consistently had the highest concentrations of ammonia, (15 mg/L 20 mg/L), significantly higher than concentrations at other sites.

Average nitrate throughout the year ranged from 0.01 ± 0.002 to 0.97 ± 0.58 mg/L, excluding the outlier site KSTP outfall, which recorded average concentrations of 4.3 ± 1.6 mg/L (Fig. 3; panel 2). Spatially, nitrate distribution followed an east-west gradient and a shore-ocean gradient, with lower concentrations in the west and farther from land. The highest concentrations of nitrate were consistently recorded within the Laucala Bay and Mataisuva area, with the KSTP outfall in Laucala Bay exhibited the highest concentrations of nitrate, ranging from 3 mg/L in August to 6.5 mg/L in November. Coastal waters along Nasilai had concentrations similar to the Suva Harbour-Namuka area (0.02 mg/L to 0.6 mg/L), while the lowest concentrations (0.008 mg/L – 0.13 mg/L) were west of Navakavu. Monthly differences showed lower concentrations in June, August, and October (Supplementary Fig. 7). However, the overall spatial distribution pattern of nitrate concentrations remained consistent with highest concentrations recorded within the Laucala Bay and Mataisuva area (0.041 mg/L to 6.5 mg/L), moderate levels along the Nasilai and the Suva Harbour-Navakavu area and the lowest concentrations (0.008 mg/L – 0.13 mg/L) west of Navakavu.

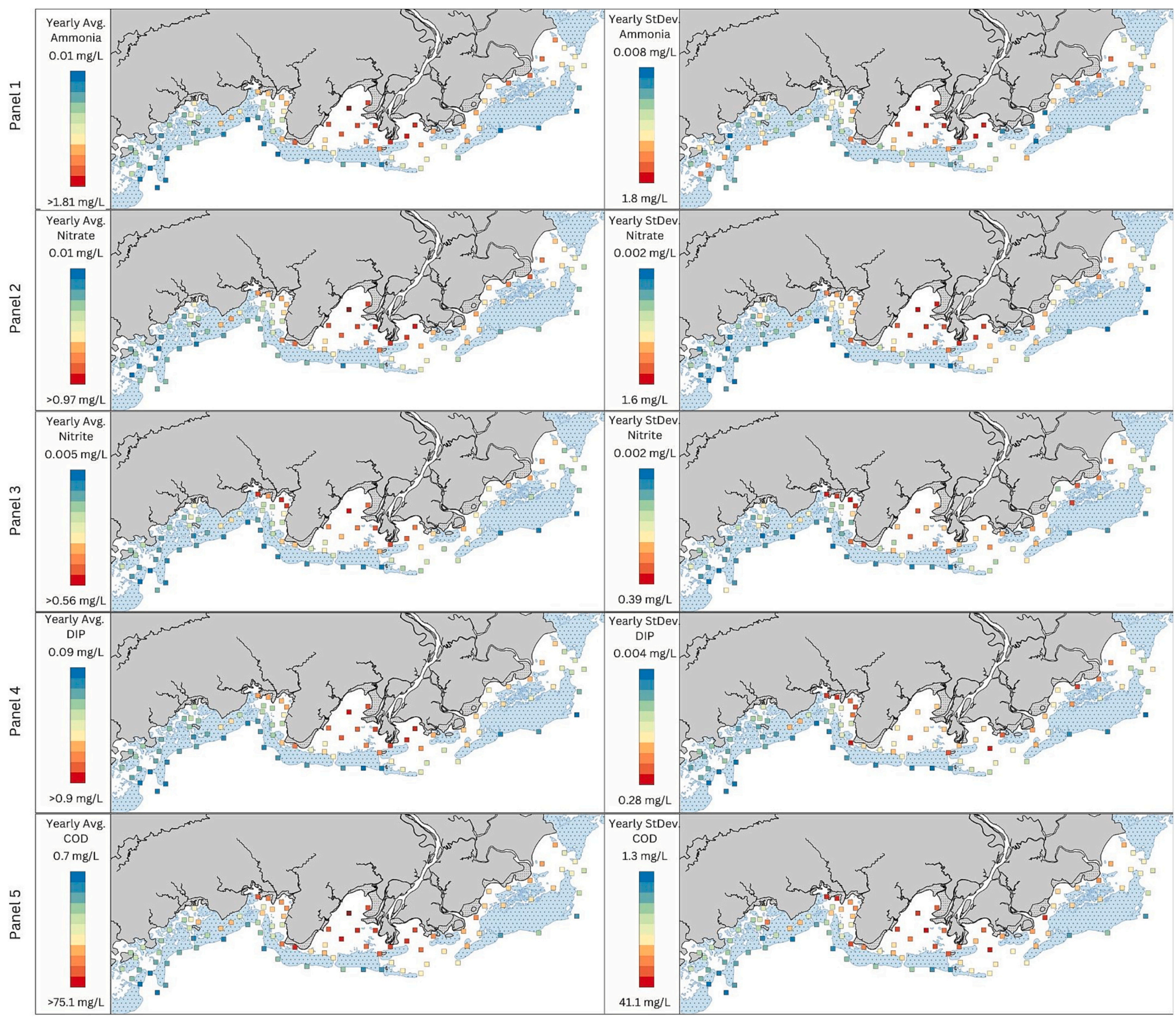

Fig. 3. Spatial distribution of annual averages (left column) and standard deviation (right column) of ammonia (panel 1), nitrate (panel 2), nitrite (panel 3), dissolved inorganic phosphate (DIP) (panel 4), and chemical oxygen demand (COD) (panel 5).

Nitrite concentrations on average ranged from 0.005 ± 0.002 to 0.56 ± 0.39 mg/L (Fig. 3; panel 3), with highest concentrations observed within the Laucala Bay, Mataisuva area, and near-shore sites at the Suva Harbour. Coastal waters along the Nasilai area generally exhibited higher concentrations (0.09 mg/L - 0.13 mg/L) compared to sites west of the Suva Harbour (0.03 mg/L – 0.17 mg/L), while the lowest concentrations were recorded along the outer reef edges towards the open ocean (0.005 mg/L - 0.02 mg/L). Monthly variations showed nitrite levels being highest in March, October and November as opposed to June August and January (Supplementary Fig. 8), however, the differences were not significant. Spatially, the distribution followed a consistent east-west and coast-ocean gradient, though peak concentrations varied by month. In March, November, and December, the highest levels (1.46–6.55 mg/L) were in Laucala Bay, while in June and August, the highest concentrations (0.05–0.71 mg/L) were near Suva Harbour. In October, peak levels (0.36–0.71 mg/L) were split between Laucala Bay and sites near the Nasilai River. Across all months, lower concentrations (0.005–0.07 mg/L) were consistently observed west of the Suva Peninsula.

Yearly average DIP concentrations ranged from 0.09 ± 0.004 to 0.9 ± 0.28 mg/L (Fig. 3; panel 4). Sites towards the west, and closer to open ocean generally had lower concentrations of DIP compared to sites along the east and closer to the shore. Highest concentrations of DIP were consistently recorded within the Laucala Bay and Mataisuva area (0.67–1.0 mg/L Nearshore sites at Suva Harbour averaged higher DIP concentrations (0.23–0.53 mg/L) compared to Nasilai (0.06–0.44 mg/L), while sites west of Suva Harbour exhibited the lowest concentrations (0.02–0.16 mg/L), even lower than Nasilai. Outer reef sites consistently recorded the lowest levels (0.02–0.04 mg/L). In terms of monthly variation, DIP concentrations were highest in March, followed by November and October, compared to June, August, and January which remained stable (Supplementary Fig. 9). Spatially, DIP concentrations remained consist east-west and coast-ocean gradients across months, with highest concentrations recorded in the Laucala Bay and Mataisuva area (0.83–1.0 mg/L), moderate levels along Nasilai, and lowest concentrations (0.02 mg/L – 0.04 mg/L) along outer reefs.

Yearly average COD concentrations ranged from 0.7 ± 1.3 to 75.1 ± 35.7 mg/L, excluding the outlier site at the KSTP outfall, which averaged 111.75 ± 41.1 mg/L (Fig. 3; panel 5). COD showed clear east-west and coast-ocean gradients, with the highest concentrations (1.6 mg/L – 92.5 mg/L) along the Nasese Channel, Laucala Bay, and Mataisuva. Coastal waters along Nasilai exhibited concentrations similar to Suva Harbour and Namuka (5.6 mg/L to 28.6 mg/L), while sites furthest west displayed lower concentrations (0.45 mg/L to 4.84 mg/L). Outer-reef sites along the west consistently recorded the lowest COD concentrations (0.01 mg/L to 2.63 mg/L). Monthly variability, (Supplementary Fig. 10), was notable, but spatial patterns remained consistent, with highest concentrations in the Laucala Bay (23.4 mg/L - 169.1 mg/L). In March, November, and January, high concentrations around Laucala Bay was more pronounced, extending into Nasese Channel, and Mataisuva, rather than being restricted within Laucala Bay.

3.3. *Wet months vs dry months*

This study observed significant differences between aggregated dry months (June, August, October) and aggregated wet months (March, November, January) for several physiochemical parameters and nutrients. These differences provide insights into the seasonal variations in the water characteristics of the study area and are explored in detail below.

3.4. *Physiochemical water properties*

Warmer temperatures were observed during the wet season, with an average range of 27.5 ± 0.09 to 29.4 ± 0.8 °C. In contrast, the dry season had relatively lower temperatures, with an average range of 25.4 ± 0.02 to 28.4 ± 0.85 °C (Figs. 4 and 5). Salinity levels were lower during the wet season, with an average range of 24.7 ± 0.04 to 34.4 ± 2.4 PSU. Conversely, the dry season exhibited higher salinity levels, with an average range of 27.2 ± 0.09 to 35.4 ± 2.19 PSU. Dissolved oxygen concentrations were lower in the wet season, ranging from an average of 6.3 ± 0.005 to 6.8 ± 0.36 mg/L. In comparison, the dry season showed slightly higher dissolved oxygen concentrations, ranging from an average of 6.4 ± 0.09 to 6.9 ± 2.1 mg/L. Higher levels of TSS were observed during the wet season, ranging from an average of 0.3 ± 0.07 to 15.1 ± 4.82 mg/L. Conversely, the dry season exhibited slightly lower levels of TSS, ranging from an average of 0.2 ± 0.1 to 14.2 ± 10.7 mg/L. No significant difference in turbidity levels were observed between the wet and dry seasons.

3.5. *Nutrient distribution*

For nutrients, seasonal differences were noted for nitrates and COD (Figs. 6 and 7). Lower concentrations of nitrates were recorded during the aggregated dry months, ranging from 0.01 ± 0.0 mg/L to 3.8 ± 2.0 mg/L. In contrast, higher concentrations of nitrates were observed during the wet months, ranging from 0.003 ± mg/L to 4.8 ± 1.8 mg/L. Lower concentrations of COD were recorded during the aggregated dry months, ranging from 0.02 ± 0.005 mg/L to 102 ± 64.6 mg/L. On the other hand, higher concentrations of COD were observed during the wet months, ranging from 1.5 ± 0.2 mg/L to 120 ± 42.0 mg/L. Ammonia, nitrites and DIP did not exhibit any distinct differences between wet and dry months.

3.6. *Relationship between variables*

3.6.1. *Correlations*

Correlations ranged from very strongly positive to very strongly negative, reflecting diverse relationships in strength and direction (Table 1). Turbidity demonstrates a very strong positive correlation with TSS ($r^2 = 0.96$), indicating a close association between these variables. Ammonia exhibits a very strong positive correlation with Nitrate (0.86), while DIP has a strong positive correlation with COD (0.81), suggesting robust associations. Strong positive correlations were observed between Nitrite and DIP ($r^2 = 0.75$) and between Nitrate and COD ($r^2 = 0.74$). Moderately positive correlations were identified for Nitrate with Nitrite ($r^2 = 0.55$), COD with TSS ($r^2 = 0.53$), and Turbidity with Nitrate, Nitrite, and COD ($r^2 = 0.53$ each). Weakly positive correlations were found between Temperature and Ammonia ($r^2 = 0.16$), Nitrate ($r^2 = 0.34$), Nitrite ($r^2 = 0.18$), DIP ($r^2 = 0.17$), COD ($r^2 = 0.33$), and TSS ($r^2 = 0.13$). Conversely, Salinity exhibited strong negative correlations with Turbidity ($r^2 = -0.82$), TSS ($r^2 = -0.81$), DIP ($r^2 = -0.70$), Nitrate ($r^2 = -0.57$), and Nitrite ($r^2 = -0.55$). Additionally, a weak negative correlation was noted between Salinity and Dissolved Oxygen ($r^2 = -0.14$). Dissolved Oxygen showed weak negative correlations with Turbidity, TSS, Nitrate, COD, DIP, Nitrite, and Ammonia ($r^2 = -0.18$, -0.18, -0.12, -0.10, -0.09, -0.09, and $-$ 0.004, respectively). These varied correlations (summarized in Table 1) provide insights into the interconnections and influences within the water quality parameters being analyzed.

3.6.2. *PCA*

Two principal components were obtained with eigenvalues greater than one, which combined explain over 89 % of the variation in water quality (Fig. 8). Accounting for 81.1 % of the variability in the data, PC1 is the most prominent component explaining variance in water quality within the study site, and characterized by strong positive relationships between temperature, turbidity, ammonia, nitrate, nitrite, DIP, COD and TSS. PC2, which contributed 8.7 % of the explained variance, is characterized by a strong positive relationship between temperature and salinity, nitrate and DIP.

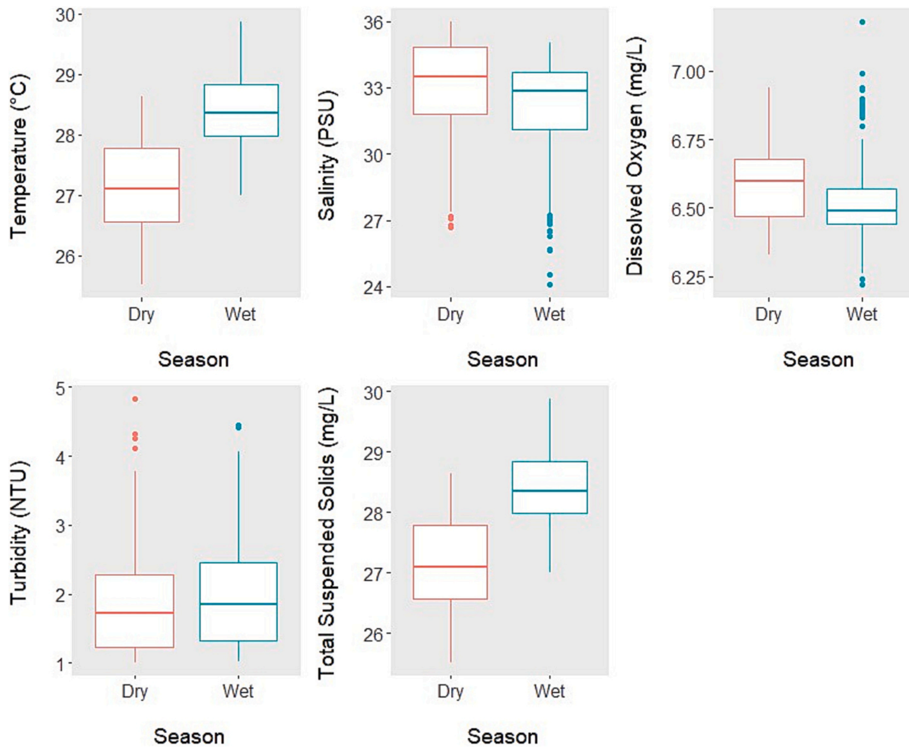

Fig. 4. Differences between wet and dry seasons of temperature, salinity, dissolved oxygen, turbidity and total suspended solids (TSS).

3.7. Spatial characterization of water quality

Six significant clusters accounting for all water quality parameters assessed were identified in this study. These clusters group the sampling sites based on similarities in the water quality data (Fig. 9). Table 2 below summarizes the sampling sites assigned to each cluster.

Spatially, the clusters formed distinct patterns that provide insights into associations between nutrient characteristics and the distribution of study sites along the GSUA coastline. With the exception of clusters 3 and 4, which show some spatial overlap (Supplementary Fig. 11) no overlap of similarities in variables is evident. Sites included within Cluster 1 stretch across the entire system from east to west and primarily comprise sites located along the outer reef towards the open ocean (Fig. 10). These sites are characterized by their proximity to the outer reef edges and their exposure to oceanic influences. A slight deviation from Cluster 1 occurs around the Makuluva reef in the Rewa Roads area, where sites fall within Cluster 2. Cluster 2 extends primarily along the back reef, starting from Makuluva and continuing through the Rewa Roads towards the Nasilai Passage and lagoon. The sites within Cluster 2 are influenced by the back-reef environments and bulk transport connectivity between the Rewa River system and the lagoon areas. Cluster 3 is split into two primary spatial compartments. The first compartment spans along the nearshore sites of the Suva Harbour, extending from the eastern end of the Navakavu peninsula to the western end of the Suva Peninsula, approximately where Walu Bay is located. The second compartment of Cluster 3 spans from the nearshore environments of Rewa Roads and extends eastwards into the Nasilai Bay and mouth. A smaller proportion of variability described by Cluster 3 are also observed within the Nasese Channel and along the eastern side of the back-reef of the Nukubuco Reef towards Nukulau. Cluster 4 represents the majority of the Laucala Bay and extends predominantly across the bay towards Mataisuva, which is adjacent to the main Rewa River mouth. Additionally, aspects of Cluster 4 are noticeable in the Nasese Channel, indicating the influence of Laucala Bay's water dynamics on nutrient distribution. Cluster 5 is represented by a single site located inside the Laucala Bay at the KSTP outfall. This site exhibits distinct nutrient characteristics and stands out as a separate cluster within the bay. Finally, cluster 6 spans from the westernmost sites towards Laucala Bay, where it transitions out of the Nasese Channel. It is primarily comprised of the back-reef and nearshore environments west of the Naqara-Namuka area, the central Suva Lagoon, and the eastern end of the Nasese Channel entering the Laucala Bay.

3.8. Water characteristic profiles within clusters

Clusters identified in this study exhibit distinct characteristics based on associations between their respective various environmental variables (Fig. 11), each with specific profiles across the GSUA. Cluster 1 is characterized by low temperature, high salinity, very low turbidity, and very low TSS. It also shows very low levels of ammonia, nitrate, nitrite, dissolved oxygen, and COD. Cluster 2, conversely, experiences relatively warmer temperatures, lower salinity, and moderate dissolved oxygen levels. Cluster 3 is marked by moderate levels of the various variables under consideration. Cluster 4 demonstrates moderately high temperatures, moderately low salinity, and average dissolved oxygen levels. It also exhibits moderately high turbidity and TSS, along with a large range of ammonia, nitrate, and moderately high nitrite and COD. Cluster 5 comprises the warmest waters across the GSUA study area with the lowest salinity, similar dissolved oxygen levels to clusters 2, 3, and 4, but it has the highest levels of turbidity, TSS, and very high levels of ammonia. Additionally, it shows the highest levels of nitrate, nitrite, DIP, and COD. Lastly, Cluster 6 is characterized by elevated temperature and high salinity, along with lower dissolved oxygen and turbidity levels, as well as lower nutrient concentrations (ammonia, nitrite, nitrate, dissolved oxygen, and COD). Overall, the clustering analysis reveals distinct groups of environmental conditions which predominate within localized areas of the GSUA coastline, each having its unique combination of temperature, salinity, dissolved oxygen, turbidity, TSS, ammonia, nitrate, nitrite, DIP, and COD levels.

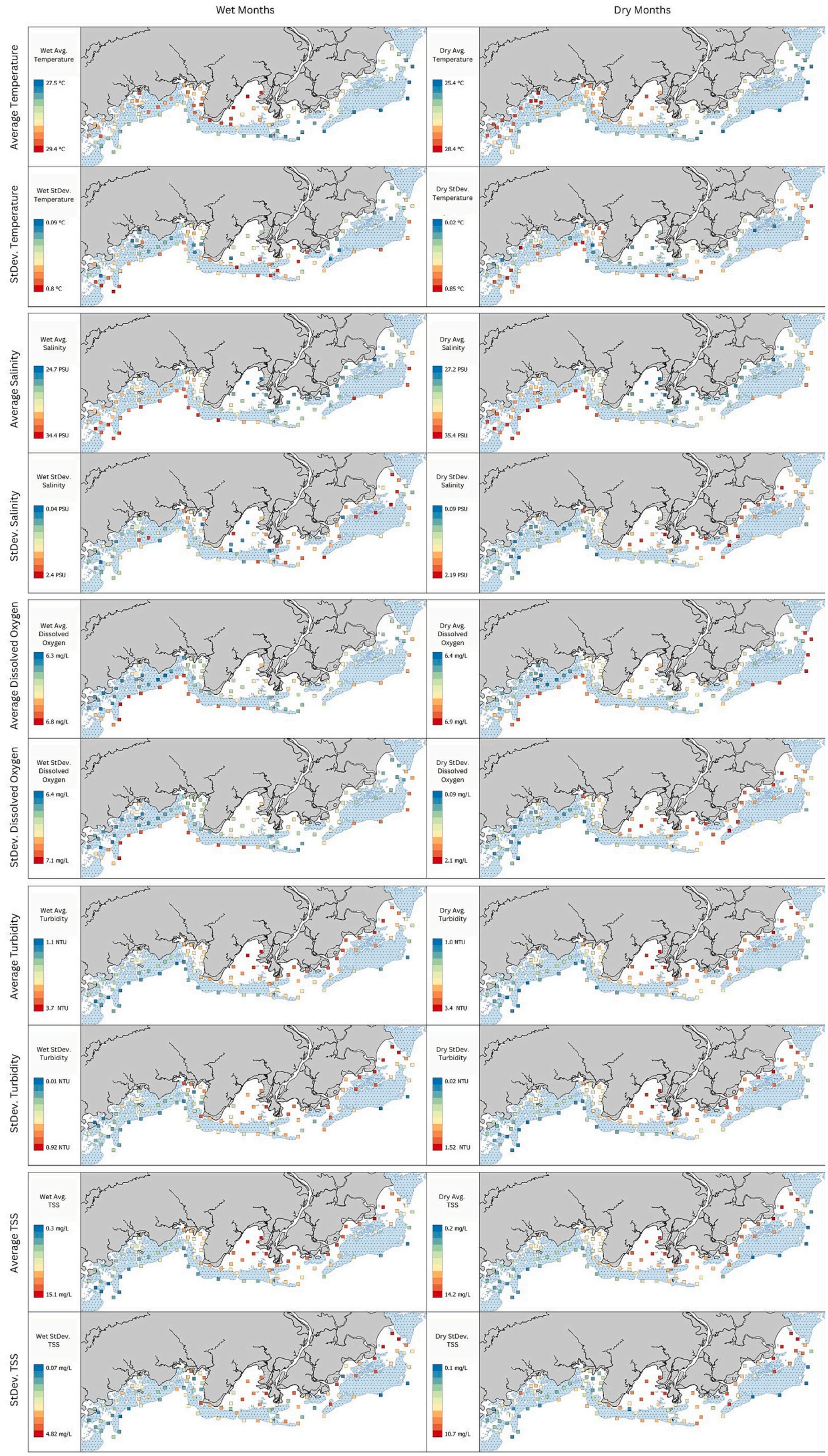

Fig. 5. Spatial distribution of average and standard deviations of temperature, salinity, dissolved oxygen, turbidity, and total suspended solid (TSS)s during wet and dry months.

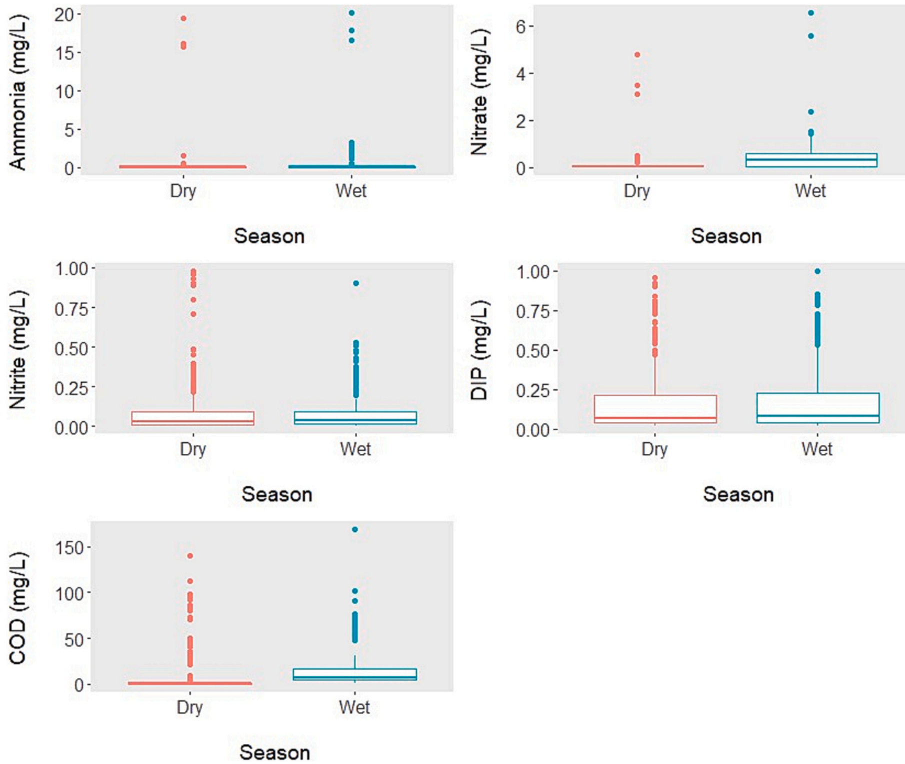

Fig. 6. Differences between wet and dry seasons of ammonia, nitrate, nitrite, DIP and CODs.

3.9. *Clustering in wet vs dry months*

The clustering analysis between aggregated wet and dry months showed no significant difference in the results (Supplementary Figs. 13 & 14). For both sets of months, the recommended number of clusters remained the same, with six clusters identified within each, respectively. The only variations observed were related to the order and distribution of sampling sites within certain clusters. One notable difference was observed during the wet months, where near-shore sites in Suva Harbour were included in the same cluster as site 43 (KSTP) in Laucala Bay (Supplementary Figs. 15 & 16). Similarly, during the wet months, a considerable portion of Suva Harbour was clustered together with parts of Laucala Bay and Rewa Roads. In contrast, during the dry months, Suva Harbour and parts of Laucala Bay were clustered with the back-reef/nearshore environments like Naqara – Namuka, resulting in a large backreef cluster extending from Laucala Bay approximately to the Nasese Channel and farther west towards Naqara. Despite these differences, the outer reef sampling sites remained consistently clustered together in both wet and dry seasons, with only sporadic events breaking the pattern. Additionally, along eastern sites from Mataisuva to Nasilai, the near-shore cluster was more pronounced during the wet season compared to the dry season. Significant differences were observed in temperature, salinity, dissolved oxygen, turbidity, ammonium, nitrate, nitrite, DIP, COD, and TSS between wet and dry seasons across various clusters. Temperature differed significantly in all clusters (e.g., Cluster 1: t (15.48) = 15.48, p = 0; Cluster 3: t (14.09) = 14.09, p = 0), with consistently higher values in the wet season. Salinity also showed significant differences in most clusters except Cluster 4 (t (−0.11) = −0.11, p = 0.9094), where no significant variation was observed. Dissolved oxygen varied significantly except in Clusters 2 (t (−1.76) = −1.76, p = 0.0819) and 5 (t (−1.6) = −1.6, p = 0.1988). Similarly, OBS showed no significant change in Cluster 4 (t (0.28) = 0.28, p = 0.7797), while other clusters displayed clear seasonal differences. Notably, nitrate levels exhibited significant differences across all clusters except Cluster 5 (t (3.12) = 3.12, p = 0.0747), and nitrite was significant in all clusters except Clusters 5 (t (0.96) = 0.96, p = 0.3868) and 6 (t (1.39) = 1.39, p = 0.1672). DIP and COD followed similar patterns, with significant differences in most clusters but not in Cluster 4 for DIP (t (−1.91) = −1.91, p = 0.0624) and Cluster 3 for COD (t (−0.96) = −0.96, p = 0.3433). Lastly, TSS differences were non-significant in Cluster 4 (t (0.86) = 0.86, p = 0.3961), while the rest showed significant variation between wet and dry seasons.

4. Discussion

This study presents, for the first time, a comprehensive and high-resolution assessment of water quality within the coastal region of the Greater Suva Urban Area (GSUA) stretching from Nasilai Bay in the east to Naqara in the west. Systematic measurements based on recurrent data collection of four physicochemical parameters, five nutrient levels, and turbidity across 97 distinct sites are reported, providing a comprehensive and high-resolution dataset and analyses covering an extensive area beyond the conventional boundaries of Suva Harbour and Laucala Bay.

This expansive baseline study contributes substantially to the growing body of evidence illustrating the profound and far-reaching impacts of urban systems on coastal marine environments, and is the most comprehensive assessment reported to date for Fiji. Moreover, it establishes a pivotal precedent for understanding urban marine environments within the Pacific Islands context, where historical data on water quality and pollution indices remain primarily confined and limited to bays directly contiguous with urban centers.

4.1. *Physical parameters*

Analysis of physical parameters observed in our study exhibit ranges that align with findings from similar tropical and subtropical coastal regions, both within the Pacific Islands and globally, and uncovered intriguing spatial patterns and seasonal variability, influenced by climatic, geographic and anthropogenic factors.

In our study, the annual temperature ranged from 26.76 ± 0.99 °C to

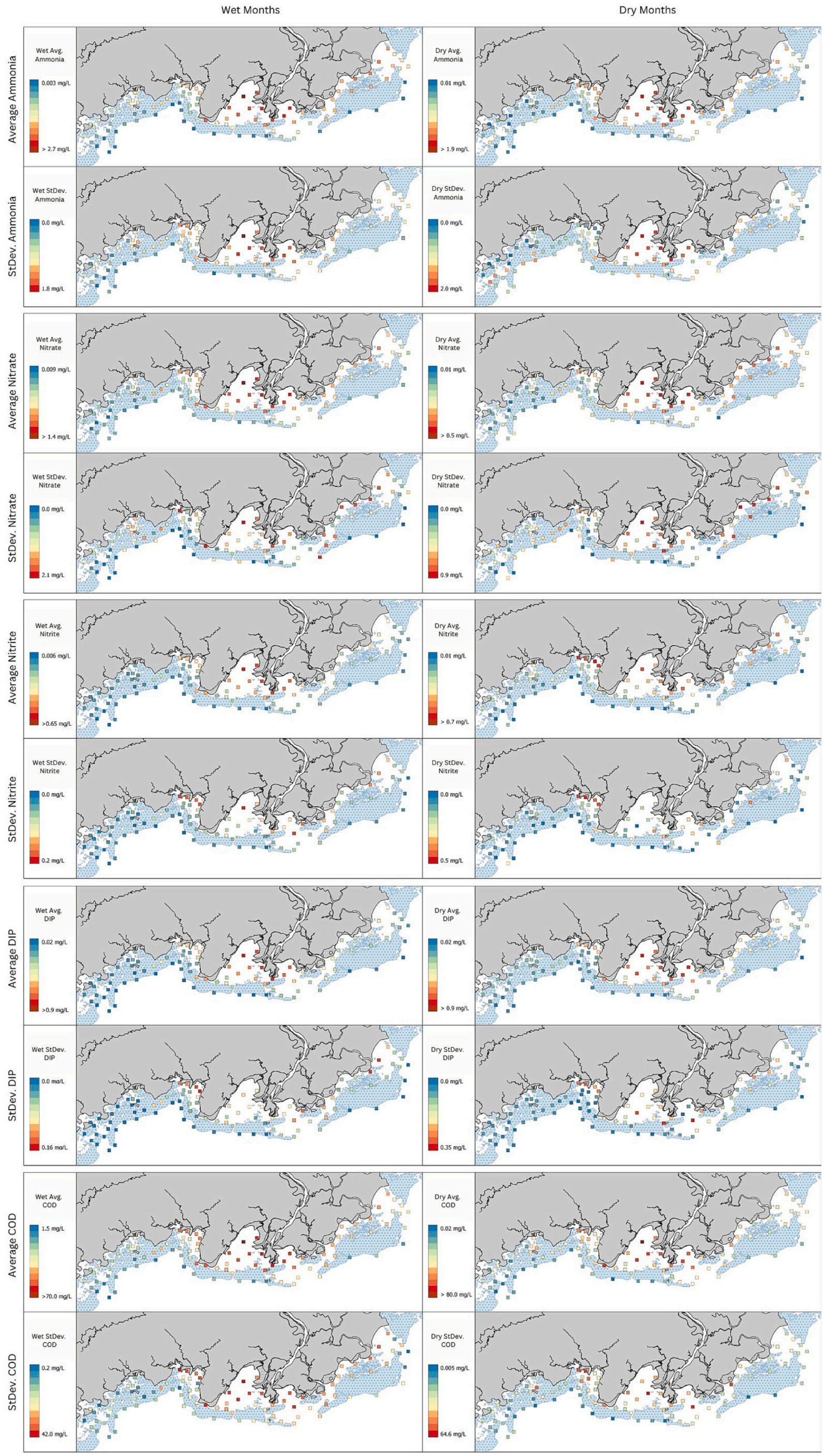

Fig. 7. Spatial distribution of average and standard deviations of ammonia, nitrate, nitrite, DIP, and COD during wet and dry months.

Table 1
Pairwise correlations between water quality parameters with Pearson's correlation coefficient (r^2) across sites sampled along the GSUA coastline. Positive correlations donated by hues of blue, while negative correlations denoted by hues of orange. The darker the hue the greater the correlation.

	Temperature	Salinity	Dissolved Oxygen	Turbidity	Ammonia	Nitrate	Nitrite	DIP	COD	TSS
Temperature	1									
Salinity	−0.20	1								
Dissolved Oxygen	−0.40	0.14	1							
Turbidity	0.11	0.82	−0.18	1						
Ammonia	0.167	−0.39	−0.004	0.33	1					
Nitrate	0.34	−0.58	−0.13	0.53	0.86	1				
Nitrite	0.18	−0.55	−0.10	0.53	0.44	0.56	1			
DIP	0.18	−0.70	−0.09	0.66	0.49	0.64	0.75	1		
COD	0.33	−0.58	−0.10	0.52	0.61	0.74	0.57	0.81	1	
TSS	0.13	0.81	−0.18	0.95	0.33	0.53	0.53	0.65	0.53	1

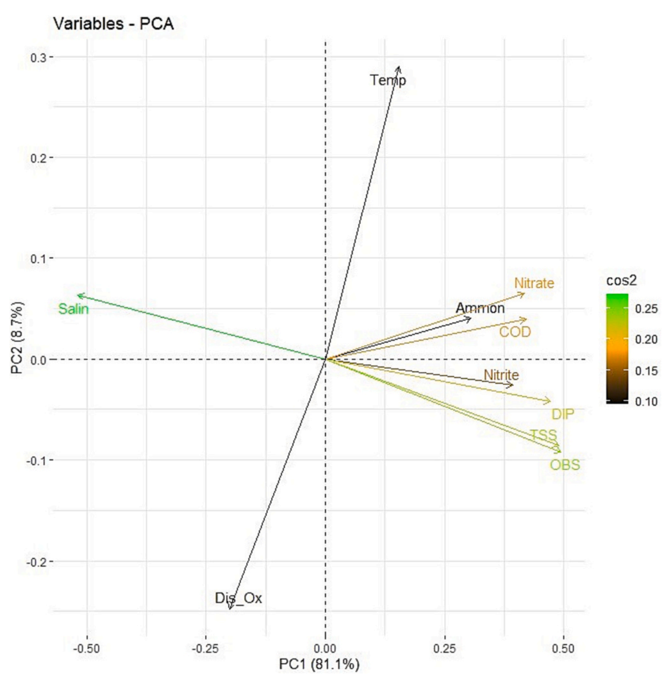

Fig. 8. Biplot of principle components 1 and 2 which explain over 89 % of variation in water quality variables. Color scale is representative of the contribution factor of each variable.

28.77 ± 0.77 °C, with extremes of 29.87 °C at the KSTP outfall in March and 25.52 °C at Nasilai Reef in August. These values are comparable to those reported for Tarawa, Kiribati (27.9–33.8 °C, Graves et al., 2021) and slightly overlap with the cooler ranges in Vanuatu (~24–27.5 °C, Devlin et al., 2020) and New Caledonia (21.3–26.65 °C, Le Borgne et al., 2010). Globally, our temperature ranges are higher than those in the South China Sea (11.10 ± 2.24 °C to 25.68 ± 1.32 °C, Liu et al., 2019) but are consistent with findings in port and harbour regions of India (22.64 ± 0.4 to 29.05 ± 1.37 °C, Gupta et al., 2005). Salinity in our study varied annually from 26.00 ± 1.46 PSU at the Vunidawa distributary to 34.80 ± 0.51 PSU at Naqara Passage. These values reflect the influence of freshwater inputs during the wet season and evaporation during the dry season. Similar patterns are evident in Tarawa (30.9–35.5 PSU, Graves et al., 2021), Vanuatu (2–36 PSU, Devlin et al., 2020), and New Caledonia (35.4–35.9 PSU, Le Borgne et al., 2010). Our results align well with global salinity ranges for tropical systems, including those in the South China Sea (29.67 ± 0.42–30.30 ± 0.25 PSU, Liu et al., 2019) and India's port regions (29.78 ± 1.04 PSU, Gupta et al., 2005). Dissolved oxygen (DO) concentrations in our study ranged from 6.40 ± 0.07 mg/L at Namuka Harbour to 6.78 ± 0.24 mg/L at the outer reef. These values are similar to those reported in Tarawa (~5.4–8.16 mg/L, Graves et al., 2021) and overlap with global comparisons, such as the South China Sea (4.62 ± 0.67 mg/L to 8.71 ± 0.53 mg/L, Liu et al., 2019) and Indian ports (4.67 ± 0.50 to 6.01 ± 1.02 mg/L, Gupta et al., 2005).

Turbidity in our study ranged from 1.10 ± 0.04 NTU to 3.50 ± 0.69 NTU, consistent with ranges observed in New Caledonia (0.5–4.0 NTU, Fichez et al., 2010). However, our values were notably lower than those in Tarawa (20 NTU, Graves et al., 2021) and India (28.8 ± 14.7 to 64.2 ± 32.0 NTU, Gupta et al., 2005). Similarly, our total suspended solids (TSS) ranged from 0.30 ± 0.15 mg/L to 14.70 ± 3.8 mg/L, falling within the ranges documented for Vanuatu (4–11 mg/L, Devlin et al., 2020) but far below the elevated levels seen in Indian ports (283.5 ± 81.8 to 356.0 ± 159.7 mg/L, Gupta et al., 2005). Overall, our findings align with established patterns for Pacific Island coastal systems and tropical regions globally, reflecting the influence of local rainfall, riverine input, and oceanographic processes. While our ranges were consistent with nearby Pacific Island studies (Tarawa, Vanuatu, and New Caledonia), they also highlight the variability in physical parameters seen in geographically distinct regions like the South China Sea and Indian coastal waters. These comparisons underscore the importance of understanding regional dynamics, including spatial and seasonal patterns in order to contextualize local observations in a global framework.

Spatial patterns across the GSUA region revealed distinct east-west and ocean-land gradients driven by both natural and anthropogenic factors. Cooler waters and lower salinity levels characterized eastern areas, such as Nasiali Reef and Laucala Bay, where ocean currents and significant freshwater inputs from the Rewa River and its distributaries dominate. In contrast, western sites, including Naqara Passage and Namuka Harbour, exhibited warmer temperatures and higher salinity due to minimal freshwater influx and restricted circulation. Urban discharge, particularly from the KSTP, amplified nearshore warming and reduced water quality in areas like Laucala Bay, where elevated turbidity, TSS, and reduced dissolved oxygen levels were observed. These spatial gradients reflect a complex interplay of oceanographic

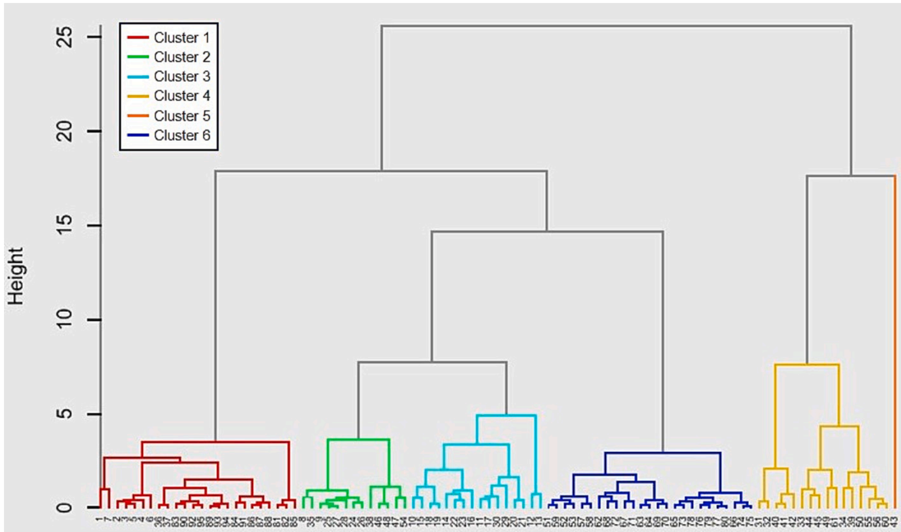

Fig. 9. Dendrogram of water quality data with hierarchical cluster analysis based on the PCA and the Ward linkage algorithm. Each cluster is defined by color.

Table 2
Summary of sampling sites assigned to each of the six clusters identified in the study based on water quality parameters. The clusters represent distinct water quality characteristics across the study area, providing insights into the spatial distribution of key water quality variables.

Cluster	Sampling sites
Cluster 1	1, 2, 3, 4, 5, 6, 7, 36, 37, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95
Cluster 2	8, 9, 24, 25, 26, 27, 28, 35, 38, 46, 47, 48, 54
Cluster 3	10, 11, 12, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 29, 30
Cluster 4	31, 32, 33, 34, 39, 40, 41, 42, 44, 45, 49, 50, 55, 56, 60, 61
Cluster 5	43
Cluster 6	51, 52, 53, 57, 58, 59, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80

processes, geographic features, and human activities. Similar trends are evident globally: in Tarawa, Kiribati, urban runoff and stagnant lagoon conditions heightened turbidity and TSS nearshore (Graves et al., 2021), while in Morocco and the South China Sea, seasonal heating and limited mixing amplified temperature variations in urbanized coastal areas (Achtak et al., 2024; Liu et al., 2019). Studies in Vanuatu also highlight the role of riverine discharge and rainfall in shaping nearshore salinity and sediment dynamics (Devlin et al., 2020). These observations emphasize the interconnected influence of natural and anthropogenic factors on coastal systems, mirroring broader patterns in tropical regions worldwide.

Seasonal patterns were prominent across temperature, salinity, dissolved oxygen (DO), turbidity, and total suspended solids (TSS), underscoring the critical role of wet and dry season dynamics, in tropical and subtropical regional across the world (Irvine et al., 2011; Romigh et al., 2006; Woldeab et al., 2018). During the wet season (January, March, and November), higher rainfall and reduced water mixing contributed to notable changes. Warmer temperatures were observed during these months, ranging from 26.76 ± 0.99 °C to 28.77 ± 0.77 °C

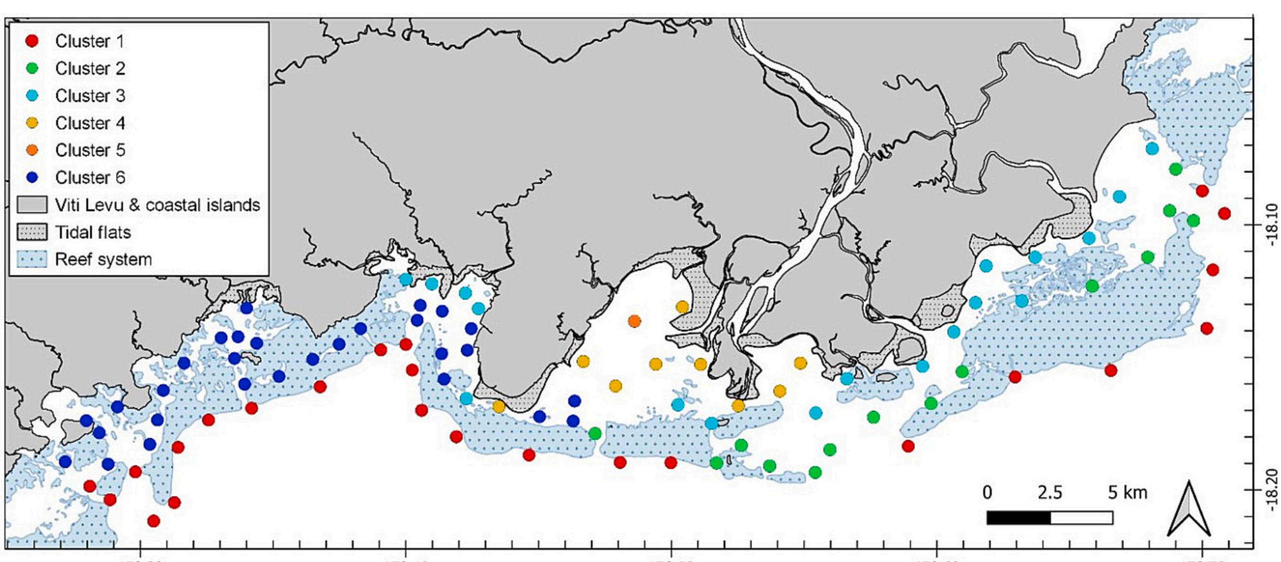

Fig. 10. Spatial distribution of water quality clusters from hierarchical clustering analysis based on with and on the PCA and the Ward linkage algorithm. Each cluster is defined by color.

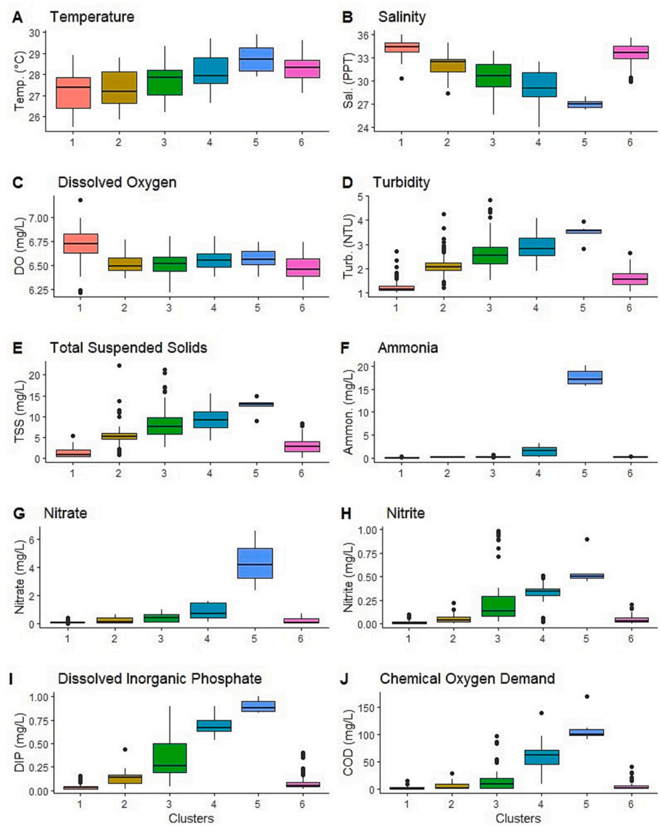

Fig. 11. Distribution of annual average environmental variables measured in each of the 6 clusters defined in Fig. 10.

peaking at the KSTP outfall in Laucala Bay. This warming effect of coastal waters aligns with studies from other tropical coastal systems, such as along Moroccan coastlines the South China Sea, where decreased water mixing and intensified solar heating during rainy periods produced similar seasonal observations (Achtak et al., 2024; Liu et al., 2019). The wet season also significantly impacted salinity, with freshwater inputs from rivers such as the Rewa reducing salinity to as low as 24.0 PSU in regions like Laucala Bay and Mataisuva. Similar seasonal reductions in salinity have been documented in Pacific islands like Vanuatu, where elevated rainfall and river discharge dilute coastal waters (Devlin et al., 2020), and in similar regions across the world such as coastal Everglades, Florida and in the Bohai Sea, where shifted between approximately 6.4–29.8 PSU and 29.67–30.30 PSU respectively between seasons. Additionally, turbidity and TSS concentrations were elevated during the wet months, with peak turbidity of 3.5 ± 0.69 NTU and TSS concentrations reaching 22.2 mg/L. This was attributed to increased sediment transport driven by rainfall and stormwater runoff, comparable to findings in Tarawa and Vanuatu, where heavy rainfall exacerbated sediment loads and nutrient input (Graves et al., 2021; Devlin et al., 2020).

In contrast, the dry season exhibited distinctly different trends. Elevated evaporation rates during these months concentrated salts in the water, leading to higher salinity levels of up to 35.5 PSU, consistent with typical tropical coastal systems (Skliris et al., 2014; Bingham et al., 2010). DO concentrations were relatively stable during the dry season, ranging from 6.4 to 6.9 mg/L, with minor fluctuations influenced by nutrient availability and water circulation. However, individual processes such as oxygen supersaturation, linked to primary productivity, and oxygen depletion due to organic matter decomposition were also observed. These processes contributed to variability in DO concentrations, particularly in nearshore zones with high organic inputs, reflecting patterns documented in Tarawa and other urbanized coastal regions (Chafik, 2001; Graves et al., 2021).

The interplay of climatic conditions and human activities was a dominant factor in shaping these patterns. Wet season rainfall amplified river discharge and sediment transport, while urbanization intensified warming, nutrient input, and turbidity in nearshore environments. For instance, Laucala Bay exhibited elevated temperatures and turbidity due to heat discharge and runoff, paralleling findings in urbanized coastal systems globally. Geographic features, including reef and lagoon morphology and ocean currents, further modulated spatial variability, particularly in temperature and salinity gradients. These results underscore the vulnerability of tropical coastal systems to both natural and anthropogenic pressures, highlighting the need for integrated management strategies to mitigate the impacts of urbanization and climate variability on coastal ecosystems.

4.2. Nutrients

In our study, ammonia, nitrite and nitrate concentrations fell within ranges typical of tropical coastal systems, closely aligning with findings from other Pacific Island countries. Ammonia levels ranged from 0.03 ± 0.01 mg/L at the outer reef stations to 0.17 ± 0.04 mg/L near the KSTP outfall, comparable to concentrations observed in Vanuatu (0.4–13.1 μg/L, Devlin et al., 2020) and Tarawa, Kiribati (1.5–20 μg/L, Graves et al., 2021). Slightly higher ammonia values were reported for the Noumea Lagoon, New Caledonia (0.1–>0.8 mg/L, Fichez et al., 2010). Nitrate and nitrite concentrations in our study ranged from 0.01 ± 0.004 mg/L at the reef stations to 0.24 ± 0.06 mg/L near urban and riverine sources, aligning with levels reported in Vanuatu (0.5–17 μg/L, Devlin et al., 2020) and Tarawa (8.5–86 μg/L, Graves et al., 2021). Slightly lower nitrate and nitrite concentrations were observed in the Noumea Lagoon (0.02–>0.16 mg/L, Fichez et al., 2010). Compared globally, our study's ammonia levels were higher than those reported for the South China Sea (0.02–0.12 mg/L, Wu et al., 2024) but much lower than concentrations found in industrialized regions such as Indian ports (5.41 ± 1.92–7.56 ± 2.1 mg/L, Gupta et al., 2005). Nitrate and nitrite levels similarly fell below those recorded in the Gulf of Mexico (0.56 ± 0.08–7.0 ± 0.1 mg/L, Cardoso-Mohedano et al., 2022) and Indian harbors (0.25 ± 0.07–0.63 ± 0.49 mg/L, Gupta et al., 2005). The temporal distribution of nutrients in this study revealed minimal seasonal differences for ammonia and nitrite concentrations, while nitrate levels exhibited notable variation between the wet and dry seasons. The lack of significant seasonal differences in ammonia and nitrite concentrations suggests that their primary sources—anthropogenic discharges and terrestrial runoff—remain relatively constant throughout the year.

Nutrient concentrations in our study exhibited clear spatial gradients driven by natural and anthropogenic influences. A distinct east-west gradient was observed, with higher concentrations in the eastern sections of Laucala Bay compared to the western regions. This pattern is primarily shaped by the Rewa River, which, along with its extensive distributary network, delivers significant terrestrial runoff to the eastern coastline. In contrast, the western sections of the bay receive comparatively less runoff due to fewer riverine inputs. This east-west disparity is further amplified by long-term oceanic currents and wave action driven by southeast trade winds, which promote flushing and dispersal in the western regions. A land-ocean gradient was also evident, with nutrient concentrations decreasing progressively offshore. Nearshore areas, particularly around the KSTP outfall and other urbanized zones, exhibited elevated nutrient levels due to localized discharges of untreated or partially treated wastewater. Ammonia concentrations, for instance, peaked at 17.8 ± 1.8 mg/L near the KSTP, far exceeding concentrations observed offshore (0.03 ± 0.01 mg/L). This gradient reflects the dilution and mixing processes as land-derived inputs dissipate into open waters. However, urban influences disrupt these natural gradients, particularly within Laucala Bay, where localized spikes in nutrient concentrations near urban outfalls obscure the broader spatial trends.

Similar spatial trends have been reported in other Pacific Island countries. In Vanuatu, nutrient enrichment is concentrated near Port Vila Bay, where stormwater drains and urban runoff introduce substantial nitrogen inputs, particularly in nearshore areas (Devlin et al., 2020). The influence of urbanization is also evident in Kiribati, where nutrient concentrations, particularly ammonia, spike in areas proximate to aquaculture zones and urban centers, with limited flushing exacerbating nutrient retention (Graves et al., 2021). Geographic structures, such as bays and lagoons, further modulate nutrient distribution by influencing water exchange and circulation. For instance, in the Noumea Lagoon, nutrient enrichment diminishes offshore due to effective flushing by ocean currents, similar to patterns observed in our study (Fichez et al., 2010). Globally, spatial nutrient gradients follow comparable dynamics but vary in magnitude depending on anthropogenic pressures and coastal configurations. In the Gulf of Mexico, nutrient concentrations are highest near agricultural runoff sources, with offshore dilution reducing concentrations (Cardoso-Mohedano et al., 2022). Similarly, in Indian ports, urban effluent contributes to elevated nearshore nutrient levels, with decreasing concentrations offshore due to dilution (Gupta et al., 2005). In Yantai Sishili Bay, China, nutrients decline from nearshore to offshore areas, reflecting the interplay of water exchange, seasonal runoff, and anthropogenic loading (Rahman et al., 2024; Wang et al., 2012). These global examples highlight the universal influence of land-sea gradients, water mass dynamics, and human activities on coastal nutrient distributions.

4.3. Water quality clusters

The clustering analysis employed in this study delineated six distinct water bodies within the GSUA based on similarities in key water quality variables. This approach revealed critical spatiotemporal patterns, highlighting areas with elevated nutrient concentrations and their potential ecological and public health implications. Cluster 1, for instance, represents offshore and outer reef areas strongly influenced by open oceanic processes, where clear (turbidity <1 NTU), cold (< 27 °C), oxygen-rich (> 6.7 mol/L), and nutrient-poor waters dominate, due to the input of northerly waves. Conversely, Cluster 6, comprising sheltered coastal waters to the west including parts of Suva Harbour and the Nasese Passage in Laucala Bay; captures warm, saline, and low-oxygen waters, indicative of poor flushing mechanisms and limited fluvial inputs, in turn resulting in reduced nutrient loads. Cluster 4 represents nutrient-enriched waters influenced by high fluvial input from numerous creeks and rivers, along with high anthropogenic pressures which are exacerbated at cluster 5 where the KSTP outfall is. These clusters reflect significantly elevated nutrient concentrations, highlighting the compounded effects of both fluvial and human-derived pressures. The dynamics of these nutrient-rich waters underscore the need for focused management interventions in these interconnected systems, particularly in areas with high anthropogenic influence. To the east of Laucala Bay, the coastal waters near the Rewa River and extending towards Kiuva are dominated by Cluster 3, characterized by moderate nutrient concentrations and limited oceanic influence, with properties (warm, low saline, turbid, low oxygen) shaped primarily by fluvial input and restricted exchange due to extensive reef systems. Similarly, Cluster 2 exhibits properties closely related to Cluster 3, reflecting nutrient-rich conditions, but with more pronounced oceanic interaction, particularly near distributaries in Suva Harbour.

The clustering approach demonstrated in this study based on similarities in water quality variables, is novel within a Pacific Island coastal setting. This methodology provides a detailed framework for assessing water quality variability and can serve as a benchmark for future studies in the Pacific Islands region. Globally, clustering techniques have also been applied to other regions. For example, Du et al. (2017) utilized hierarchical cluster analysis to classify coastal waters of the Bohai Sea and North Yellow Sea in China, revealing four clusters and their relationships to spatial and temporal nutrient dynamics. Comparatively, the six clusters identified in this study offer more granularity, possibly due to the diverse ecological and anthropogenic pressures characteristic of the GSUA. Similar to the findings reported for Suva here, Du et al. (2017), noted significant correlations between anthropogenic influences and nutrient enrichments, particularly in areas near riverine inputs and urban developments. The application of clustering in water quality assessments is further highlighted in studies including Awad and El-Sayed (2021), who in the Mediterranean Sea employed clustering to identify regions with varying pollution levels, emphasizing the role of anthropogenic pressures and natural processes in shaping water quality. Similarly, the application of clustering in the Baltic Sea by Andersen et al. (2017) identified hotspots of eutrophication, guiding targeted interventions. The integration of clustering with nutrient data, as demonstrated in these global examples, parallels findings in Suva; where elevated nutrient concentrations are linked to urban runoff and wastewater discharge.

Previous research on the water quality of Suva's coastal system, reported that increased turbidity and nutrient levels were closely tied to urban runoff and wastewater discharge (Lal et al., 2021) emphasizing the significant impact of human activities on water quality. Lal et al.'s (2021) observations align well with relationships reported for Clusters 4, 5 and 6 in our study, emphasizing the significant impact of human activities on water quality within Suva's waters. However, the cluster-based approach used here extends these findings by providing a more structured framework for spatiotemporal analysis, enabling a clearer understanding of water body interactions and management priorities. By leveraging clustering-based analyses, policymakers can design monitoring and intervention strategies that reflect the unique challenges of the GSUA, ensuring sustainable marine resource use, enhanced public health, and ecosystem resilience.

This framework also provides critical insights for other Pacific Island regions, where similarly high urban pressures on marine environments exist, such as semi-enclosed lagoons and atolls (Duvat et al., 2021; Varea et al., 2020). Examples include Tarawa in Kiribati and Funafuti in Tuvalu, where urbanization has led to significant nutrient pollution, along with urban centers like Port Vila in Vanuatu and Port Moresby in Papua New Guinea, which face escalating anthropogenic impacts (UNFPA, 2014). Beyond urbanized areas, the methodologies employed here could be adapted to regions where land-use changes, such as deforestation and farming, have driven increases in sediment and nutrient runoff (Bierman et al., 2009). In Fiji, this includes coastal waters near sugar processing hubs like Labasa and Lautoka; where tourism-related infrastructure is concentrated such as along the coral coast on Viti Levu and Yasawa-Mamanuca Island groups; as well as where commercial and subsistence farming activities predominate, such as along the north-eastern and southern coasts of Viti Levu, and Vanua Levu, respectively (Avtar et al., 2022; Cornelio, 2021; Naidu et al., 2017; Sachan and Krishna, 2021).

While this study provides valuable baseline insights, it has several limitations that highlight opportunities for improvement in future assessments. The temporal scope, restricted to a single year during a La Niña episode, may not capture inter-annual variability, such as those driven by El Niño conditions. Extending the study duration to include multiple years would provide a more robust understanding of long-term trends in water quality. Spatially, finer-resolution sampling in dynamic zones such as river mouths and reef passages is needed to capture more detailed patterns, while continuous monitoring during episodic events such as heavy rainfall or storm surges would enhance the temporal resolution of nutrient data. Additionally, the study's focus on nutrient pollution does not encompass other significant anthropogenic inputs, such as plastics, chemical pollutants, land reclamation, or coastal infrastructure development. Addressing these factors is essential for a more holistic understanding of water quality dynamics.

To address these gaps, the establishment of a comprehensive water quality monitoring program for the GSUA is essential. This program should include real-time in situ monitoring systems strategically placed in high-impact areas to track changes in key water quality parameters. Integration of baseline data into marine spatial planning will ensure sustainable development and resource use, while mitigating environmental degradation. Public awareness campaigns should highlight the impacts of nutrient pollution and the interconnectedness of coastal and marine systems. Targeted regulatory frameworks focusing on wastewater management and urban runoff will be crucial to reducing anthropogenic pressures. Furthermore, research on the ecological impacts of nutrient enrichment, such as its effects on coral reefs and fisheries, is necessary to guide conservation and management efforts. Regional collaboration with international partners will be vital for capacity building and addressing shared challenges, ensuring that GSUA and other Pacific Island coastal systems are better equipped to face the pressures of urbanization and climate change.

5. Conclusion

In conclusion, this study provides a comprehensive analysis of water quality variations within the GSUA, offering critical insights into the spatial and temporal dynamics influenced by both natural and anthropogenic factors. By analyzing physical parameters, nutrient levels, and turbidity across 97 sites, and identifying six distinct water quality clusters, this study highlights the intricate interplay of natural and anthropogenic factors shaping these tropical coastal environments.

Spatial gradients, rather than seasonal trends, are the primary drivers of variability in water quality across the GSUA. While seasonal changes did influence localized physicochemical properties like temperature, salinity, and turbidity; spatial factors—shaped by long term climatologies like trade winds, currents, geography as well as urban pressures like wastewater discharge and runoff—have a stronger impact on both physiochemical properties and nutrient concentrations. Urbanization, particularly from the KSTP and stormwater runoff, exacerbated these trends, underscoring the vulnerability of nearshore environments to human pressures. These spatial patterns, particularly in areas with limited water circulation, mirror trends observed in other Pacific Islands including Kirbati and Vanuatu, emphasizing the need for targeted management strategies focused on spatial factors to address ongoing anthropogenic impacts.

The clustering analysis delineated six distinct water quality clusters across the GSUA, reflecting spatiotemporal patterns of nutrient enrichment and physical conditions. Offshore areas exhibited nutrient-poor, oxygen-rich waters driven by oceanic currents, while coastal zones near river mouths, urban centers, and the KSTP outfall showed nutrient-enriched conditions. These clusters highlight the compounded effects of fluvial and human-derived pressures, such as wastewater discharge and urban runoff. Intermediate clusters near Laucala Bay and the Rewa River featured moderate nutrient levels shaped by fluvial inputs and reef systems.

The identification of distinct water quality clusters has enhanced our understanding of the ecological and public health challenges facing these coastal systems, particularly in relation to nutrient pollution, urban runoff, and fluvial inputs. These findings emphasize the pressing need for targeted management interventions, particularly in areas where human activities intersect with sensitive marine environments. By leveraging the clustering approach, this research offers a valuable framework for future water quality monitoring and management strategies, not only for the GSUA, but also for other Pacific Island regions facing similar pressures. Going forward, continued monitoring, cross-disciplinary research, and regional collaboration will be essential in addressing the evolving challenges posed by urbanization, climate change, and sustainable resource management. This study underscores the importance of integrating science, policy, and community engagement to safeguard the long-term health and resilience of Pacific Island coastal ecosystems.

CRediT authorship contribution statement

Jasha Dehm: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Romain Le Gendre:** Supervision, Conceptualization. **Monal Lal:** Writing – review & editing. **Christophe Menkes:** Supervision, Conceptualization. **Awnesh Singh:** Writing – review & editing, Supervision, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT/OpenAI in order to refine sentence structure and improve grammar. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary data

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Data availability

Data will be made available on request.

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