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Coastal water quality improves during the COVID-19 pandemic: Maui, Hawai'i

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ABSTRACT

Coastal ecosystems are increasingly threatened by degraded water quality linked to agriculture, wastewater and changes in land-use. This study collected coastal water quality measurements to assess spatiotemporal trends and drivers of variability on the island of Maui, Hawai'i. We also utilized Hawai'i's COVID-19 visitor quarantine, which dropped visitor numbers on Maui by >99 %, to evaluate the effects of population on coastal water quality. Nitrate and turbidity were highest on the north shore and during the winter. This trend is likely driven by a combination of fertilizers associated with agriculture and nearby wastewater injection wells, and large swells, respectively. All sites exceeded the State's water quality standard (WQS) for turbidity, and many sites exceed the WQS for nitrate. During the COVID-19 pandemic, coastal water quality improved across many sites, which is likely related to the visitor population reduction and stay-at-home orders that resulted in limited use of beaches and roads.

1. Introduction

Hawai'i's coral reefs provide food, coastal protection, cultural services, and economic revenue valued at $360 million a year (Cesar and Van Beukering, 2004). Despite their importance, coral reefs are threatened by a myriad of global (e.g., ocean acidification and warming) and local (e.g., eutrophication, overfishing and sedimentation) stressors that have led to a decline in overall reef health by reducing coral cover, growth and calcification rates, and increasing abundance of fleshy algae (Rogers, 1990; Hoegh-Guldberg et al., 2007; Prouty et al., 2017; Cochran et al., 2014). On Maui, state monitoring efforts reveal up to 90 % reduction in coral cover since the early 2000s, particularly on the north shore (Division of Aquatic Resources, D. S. of H, 2023).

The majority of Maui island-based studies have focused on coastal water quality, marine ecosystem and reef-scale impacts on the south and west shores, with few existing for the north shore (Prouty et al., 2017, 2018; Dailer et al., 2012; Glenn et al., 2013; Bishop et al., 2017; Miller-Pierce and Rhoads, 2016; Dailer et al., 2010). Combined, these studies reveal that turbidity and nitrogen levels consistently exceed the Hawai'i Department of Health (HI-DOH) water quality standards, with the latter being attributed to agriculture and wastewater pollution from cesspools and injection wells (Prouty et al., 2017, 2018; Bishop et al., 2017; Miller-Pierce and Rhoads, 2016; Dailer et al., 2010). Historically, sugar cane and pineapple have been the major agricultural contributors in Hawai'i (La Croix, 2021; Coulter, 1934). The fertilizers used in crop cultivation leach into the groundwater, which causes elevated nutrient loads in submarine groundwater discharge (SGD) and receiving coastal waters (Bishop et al., 2017). Presently, there are over 12,000 cesspools on Maui that must be converted to septic by the year 2050 (Mezzacapo et al., 2020). Cesspools release untreated sewage into groundwater and adjacent coastal waters leading to eutrophication and algal blooms in nearshore environments (Bishop et al., 2017; Dailer et al., 2010).

Maui county owns and operates injection wells located in Kahului (north Maui), Lahaina (west Maui) and Kihei (south Maui), and there are 26 private injection wells located in Ma'alaea (south Maui) (Dailer et al., 2010). Wastewater associated with these injection wells has been detected in Maui's nearshore waters through several mechanisms (Prouty et al., 2017, 2018; Dailer et al., 2012; Glenn et al., 2013; Bishop et al., 2017; Miller-Pierce and Rhoads, 2016; Dailer et al., 2010; Swarzenski et al., 2017). Nearshore macroalgal samples collected near the county's wastewater treatment plants showed elevated $\delta^{15}N$ values due to wastewater contributions (Dailer et al., 2010). Glenn et al. (2013) conducted a tracer study and confirmed that treated wastewater injected at the Lahaina Wastewater Reclamation Facility (LWRF) emerged as

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SGD at Kahekili Beach Park approximately three months later. Subsequently, Prouty et al. (2017, 2018) characterized the SGD at Kahekili as eutrophic (nitrate, $NO_3^- > 100$ μmol L^{-1}) and acidified (pH = 7.5) and found that coral reef ecosystem metabolism near the SGD seeps shifts toward calcium carbonate ($CaCO_3$) dissolution and respiration during periods of enhanced SGD flow. On Maui's south shore, high nutrient concentrations were measured at coastal sites near the Kihei wastewater reclamation facility (Miller-Pierce and Rhoads, 2016), but the direct effects of wastewater pollution and eutrophication on coral reef health in the area remain unknown.

Runoff and coastal erosion lead to high turbidity levels and sedimentation, which can reduce coral cover, growth rates, recruitment and photosynthesis, and may lead to degradation of the entire coral reef framework (Rogers, 1990; Rogers and Ramos-Scharrón, 2022). Massive coastal sediment plumes following storm events occur several times a year in Maui's nearshore environments. Sediment plumes are linked to poor agricultural practices, eroding stream banks, and residential and commercial development (Jonathan Stock and Cerovski-Darriau, 2020). The August 2023 Maui wildfires in Kula and Lahaina, which burned almost 7000 acres of urban and rural area, will likely exacerbate sedimentation, runoff, and other water quality stressors linked to historical agriculture and poor wastewater management on the south and west shores (Prouty et al., 2014).

The purpose of this study is to provide an island-wide assessment of temporal and spatial coastal water quality trends on Maui. In March 2020, a statewide COVID quarantine reduced Maui's visitor population by 99.5% (Hawaii Tourism Authority, 2020), providing a unique opportunity to assess the impacts of population and tourism on coastal water quality. Therefore, we expect the reduction in human activity and water use will drive water quality improvements in areas impacted by wastewater. Studies to assess coastal water quality trends following the August 2023 Maui wildfires are underway. The present study will serve as an important baseline dataset for which these, and other future studies focused on assessing impacts of watershed practices to nearshore water quality may reference.

2. Methods

2.1. Study site description

This study was conducted in coastal waters (0 to ~2 km offshore) surrounding the island of Maui, Hawai'i (Fig. 1). Percent coral cover is variable with the highest average percent coverage (45 %) observed in southwest waters near the 'Āhihi-Kīna'u Natural Area Reserve (Division of Aquatic Resources, D. S. of H, 2023). Streams and estuaries also influence Maui's coastal water quality but urbanization, channelization of streams and diversion of water flow has caused significant degradation of stream water quality and habitat and associated nearshore ecosystems.

Prevailing surface winds on Maui are northeasterly (i.e., tradewinds), with maximum rainfall occurring on windward (east) facing slopes and drier areas occurring on the leeward (west) facing slopes (Giambelluca et al., 2013; Frazier and Giambelluca, 2017). Hawai'i is characterized by a dry season (May through October) and wet season (November through April), with this cooler period experiencing less frequent tradewinds. West and south Maui are protected by nearby surrounding islands (Kaho'olawe, Moloka'i and Lāna'i) and therefore experience low wave energy relative to north and east shores that are more exposed to large swells (typical Hawai'i wave heights of 1.5 to 6 m) generated by winter storms in the northern hemisphere (Field et al.,

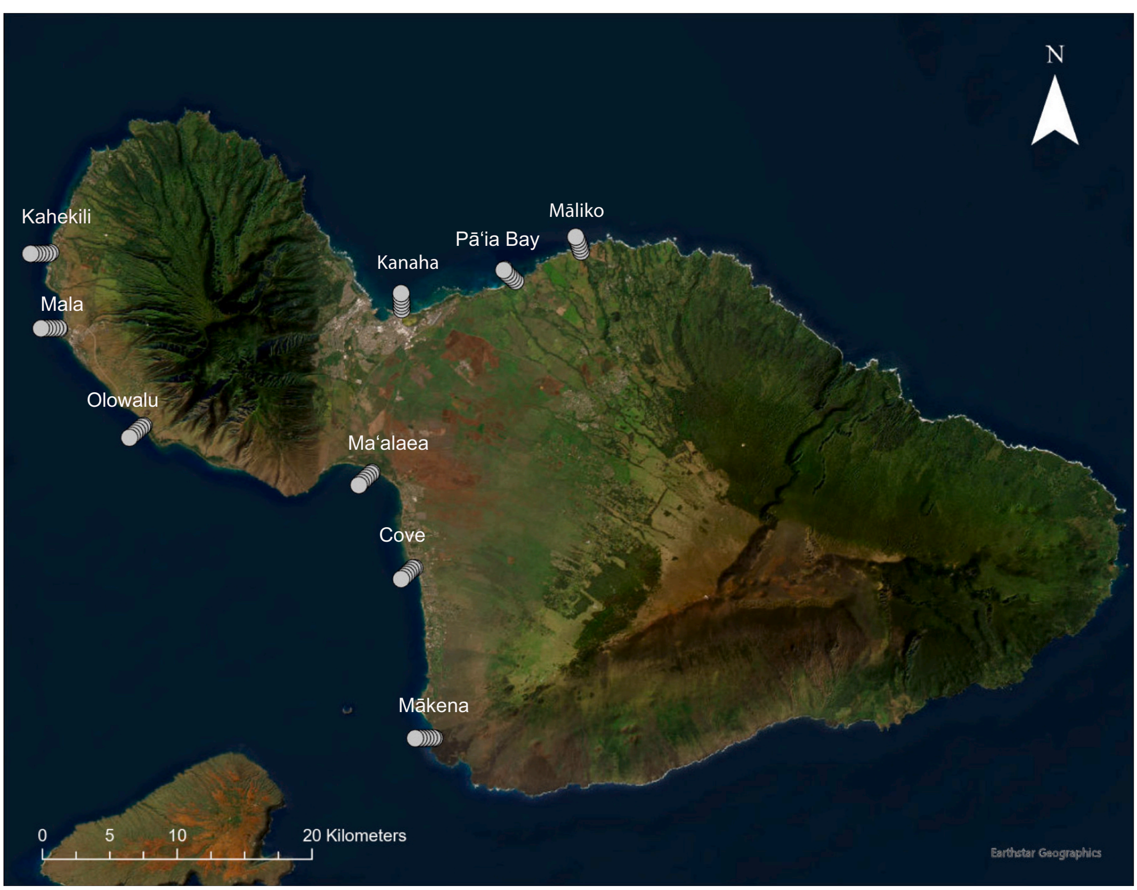

Fig. 1. Sampling sites were located within nine transects located on the north (Kanaha, Pā'ia Bay, Māliko), west (Kahekili, Mala, Olowalu) and south (Ma'alaea, Cove and Mākena) shores of Maui.

2019; Rooney et al., 2003). Hawai'i's south swells (<1 to 3 m) are generated in the summertime by storms in the southern hemisphere, although winter Kona storms (i.e., Kona lows) may also generate larger south swells (Rooney et al., 2003; Rooney and Fletcher, 2005).

Surface water samples were collected along nine transects located on Maui's north (Māliko, Kanaha and Pā'ia Bay), west (Kahekili Beach Park, Mala and Olowalu) and southwest (Ma'alaea, Cove, Mākena) shores. The transects at Kahana, Ma'alaea and Cove were chosen as sites potentially impacted by wastewater associated with injection wells. The east Maui shoreline is rugged, remote and primarily composed of basaltic rock and sea cliffs (Feirstein and Fletcher, 2004; Eakins and Robinson, 2006). For this reason, Maui's east shore was not included in this study due to lack of accessibility. Dailer et al. (2010) used $\delta^{15}N$ of algal samples to map sources of pollution across the entirety of Maui's coastlines and found the lowest $\delta^{15}N$ in east Maui (range = 0.009 ‰ to 1.62 ‰) suggesting low anthropogenic impact in this region. Each transect started as close to shore as possible and consisted of seven stations located approximately 0.5 km apart. This sampling approach resulted in 63 coastal stations with water depths that range from approximately 1 m to 45 m.

2.2. Water quality sampling

Field sampling occurred in summer 2020 (July 13–15), winter 2020–2021 (December 23–February 8) and summer 2021 (September 10–29). The timing of field sampling was chosen to encompass seasonal (winter vs. summer) variability as well as potential water quality improvements associated with Maui's mandatory COVID visitor quarantine. Transects were grouped according to their locations (north, west and south) so that each location was sampled within the same day. Every effort was made to reduce the sampling time between locations (e.g., all locations completed within a few days) but environmental conditions such as swell and wind were limiting forces, particularly in the winter.

At each station, water samples were collected at 1 m depth for a suite of water quality parameters. Temperature (accuracy = ±0.35 °C), salinity (accuracy = ±1 %) and dissolved oxygen (DO; accuracy = ±2 %) were measured using a multiparameter probe (*YSI Pro Plus*) calibrated for salinity and DO at the beginning of each day and turbidity was measured using a *Hach 2100Q* (accuracy = ±2 %) calibrated quarterly. Water samples for dissolved inorganic nutrients (nitrate+nitrite (NO_3+NO_2), hereafter referred to as nitrate or NO_3, nitrite (NO_2), silicate (SiO_2), phosphate (PO_4), and ammonia (NH_3)) were collected into 60 ml acid-washed bottles, pre-rinsed with site water three times, stored on ice and placed in the freezer (−20 °C) once back in the lab. Nutrients were analyzed on a colorimetric segmented flow analyzer (AA3, Seal Analytical) within 28 days of collection using the methods of Armstrong et al. (1967) for nitrate and nitrite, Murphy and Riley (1962) optimized by Zhang for phosphate (Zhang et al., 1999), Grasshoff et al. for silicate (Grasshoff et al., 1983) and fluorometric detection for ammonia (Holmes et al., 1999). Uncertainties associated with duplicates were calculated using relative percent difference and indicates precision of 17 % for NO_3, 12 % for NO_2, 19 % for SiO_2, 30 % for PO_4 and 21 % for NH_3.

2.3. Environmental data

Coastal water quality is linked to environmental drivers such as precipitation, wind, and wave height (De Carlo et al., 2007; Storlazzi et al., 2004; Presto et al., 2006). To evaluate seasonal, annual, and spatial trends across sites, we utilized the following datasets for the years 2020 and 2021. Wave heights were downloaded from PacIOOS (http://www.pacioos.hawaii.edu) buoy stations located at Pauwela, Lāna'i southwest and Pearl Harbor, which are the closest stations that contain the most complete representations of wave conditions on the north, west and south side of Maui, respectively, during this study. Precipitation and wind data were downloaded from the PacIOOS Weather Research and Forecasting (WRF) model, which provides a 6-day, hourly forecast at approximately 6 km resolution. Wind speeds are given at 10 m above the sea surface.

2.4. Statistical analyses

All statistical analyses were performed in Matlab and R (version 4.3.3) (R Core Team, 2024). We used ANOVA to test for significant differences in the various parameters between time (summer 2020, winter 2020–2021 and summer 2021) and location (north, west, south). We then performed a multiple comparison test against a control group using Dunnett's test, and compared results to the pairwise comparison results from Tukey's honestly significant difference test. Principal component analysis (PCA) on Euclidean distance was performed on scaled and centered matrix of water quality parameters using *prcomp* in the stats package. Water quality parameters with significant correlations ($p < 0.05$) with PC-axes were plotted as vectors on PCA ordinations. Permutational analysis of variance (PERMANOVA) was performed on Euclidean distances to test for differences among groups (direction or season-year) using *vegan* (Oksanen et al., 2022) with pairwise contrasts with Hochberg adjusted *p*-values in *pairwiseAdonis* (Martinez Arbizu, 2020). Tests of among group betadispersion (among group homogeneity of variance) were performed using betadisp in *vegan*.

3. Results

The COVID-19 visitor quarantine was imposed from March 2020 to October 2020 and greatly reduced Maui's population during this time (Currie et al., 2023) (Fig. 2, https://dbedt.hawaii.gov/). The summer 2020 sampling period reflected visitor numbers of 22,562, which is an approximate 96 % reduction in the visitor population. During winter sampling, visitor numbers reflect a rebounding population (214,351) but are still less than the summer 2021 sampling period (505,861) and a decline from previous winter seasons (~75 %). As a result of the visitor decline, Maui's wastewater treatment plants in Kihei and Lahaina both show ~70 % reductions in the amount of wastewater injected, while the Kahului Wastewater Reclamation Facility (KWRF) only injected ~15 % less wastewater during this time (Fig. 2).

Temperatures ranged 23.9–27.6 °C, with the winter (mean ± SD; 25.3 ± 0.1 °C) and three north shore sites (Kanaha, Maliko and Pā'ia Bay; 25.3 ± 0.1 °C) showing significantly ($p < 0.005$) lower average temperatures (Table 1). Mean salinity (range = 33.45–38.71) was also significantly lower in the winter (34.5 ± 0.1) relative to summer (34.8 ± 0.1) but not significantly different across locations (e.g., north, south, west). Dissolved oxygen ranged from 4.93 to 7.81 mg L^{-1}, showed no significant difference across transects, but was significantly lower in summer 2020 relative to winter and summer 2021 (Table 1). Turbidity (range = 0.25–3.48 NTU) was consistently and significantly higher at the north shore sites (1.00 ± 06 NTU) and significantly lower in summer 2020 (0.54 ± 0.06) while the COVID quarantine was in effect (Table 1).

Nitrate ranged from <0.06 to 5.49 μmol L^{-1} and was 4.4 times higher on the north shore (relative to south and west) (Table 1). Silicate (range ≤ 0.08–60.62 μmol L^{-1}) showed no significant difference between sites or seasons, but the highest average concentrations were generally found on the north shore (6.95 ± 1.18 μmol L^{-1}) (Table 1). Ammonia ranged from <0.09–2.66 μmol L^{-1} with significantly higher average concentrations found in summer 2021 (0.31 ± 0.04 μmol L^{-1}) (Table 1). Spatially, the highest average ammonia concentrations across transects occurred in south Maui (0.25 ± 0.04), as well as a north Maui site (Māliko) (0.19 ± 0.09 μmol L^{-1}). The average ammonia concentration across all other sites was at or below the detection limit. Average phosphate (range ≤ 0.01–0.24 μmol L^{-1}) across seasons and transects was near or below detection limits, with slightly higher values identified at some south shore sites (specifically, Cove and Ma'alaea) and a north Maui (Māliko) site in summer 2021.

The Hawai'i State Water Quality Standards (WQS) is an effect of the

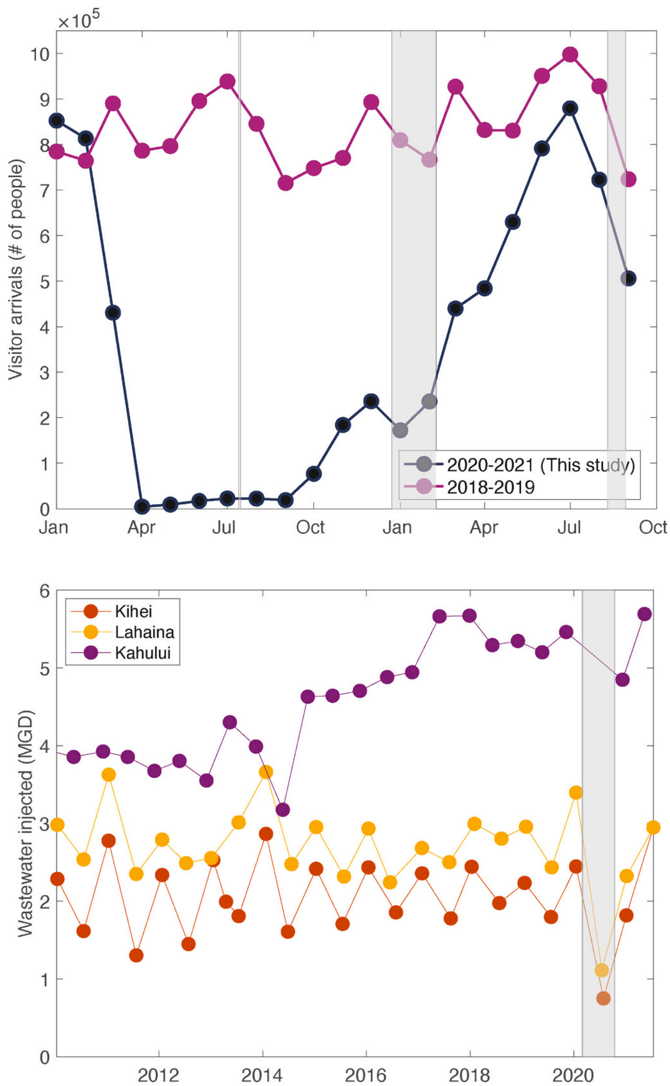

Fig. 2. Visitor arrivals from Jan 2020–Sep 2021 (black) and visitor arrivals two years prior (Jan 2018–Sep 2019, pink) for comparison. The shaded gray areas reflect the sampling periods of summer 2020 (07/13–07/15), winter 2020–2021 (12/23/2020–2/8/2021) and summer 2021 (9/10–9/29) (top). Wastewater injected (mgd) from 2011 through 2021 at the Kihei (orange), Lahaina (yellow) and Kahului (purple) wastewater reclamation facilities. The shaded gray area indicates the timing of the COVID-related visitor quarantine (bottom). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Clean Water Act and upheld by the HI-DOH (Department of Health, 2021). WQSs are separated into wet and dry season criteria for open coastal waters and should not exceed 0.35 μmol L^{-1} (wet) and 0.25 μmol L^{-1} (dry) for nitrate and 0.50 NTU (wet) and 0.20 NTU (dry) for turbidity. The average turbidity in this study exceeded both the dry and wet criteria for all transects and seasons, including in summer 2020 when the visitor population was reduced by >99 % (Figs. 2 and 3). Mean nitrate concentrations at all south (0.15 ± 0.09 μmol L^{-1}) and west Maui sites (<0.06 μmol L^{-1}) were below the WQS, except for Ma'alaea (winter) and Cove (summer 2021), two locations influenced by injection wells (Fig. 4). On the north shore, Māliko exceeded the nitrate WQS in summer, but not winter (Fig. 4). Nitrate concentrations at Pā'ia Bay exceeded the WQS in winter and summer 2020, and Kanaha nitrate exceeded the WQS in summer 2020 (Fig. 4).

Principal component analysis of water quality parameters showed the first two principal components explain 42.3 % of the variance in water quality among season and direction (Fig. 5A–B). PC1 (25.7 %) correlated with nitrate, turbidity and silicate in winter and the north shore sites. PC1 also separates phosphate and ammonia, which were primarily higher in summer 2021 and the north and south sites. PC2 (16.6 %) generally correlates with high salinity and temperature at the west and south sites and during summer seasons (Fig. 5C). PERMANOVA showed significant effects for direction ($p = 0.001$), season ($p = 0.016$), and their interaction ($p = 0.011$), with the most variance explained by direction ($R^2 = 0.138$) (Table 2). Betadispersion was different among all groups ($p = 0.010$), and pairwise tests using Hochberg-adjusted p-values showed all seasons ($p = 0.001$) and directions differed from each other ($p \leq 0.045$).

Wave heights ranged 0.32–4.00 m (0.89 ± 0.23 m) on the south, 0.51–2.30 m (0.97 ± 0.20 m) on the west, and 0.52–6.20 m (1.98 ± 0.70 m) on the north shore (Figs. 6, S1). Mean wave heights for each direction were significantly different across the entire study period, with

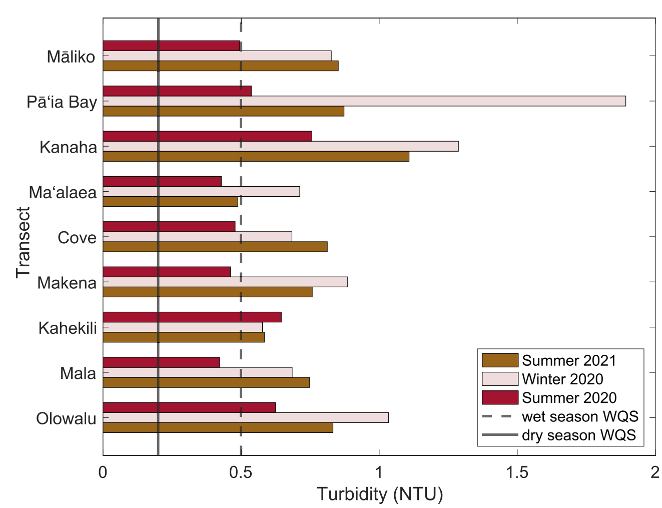

Fig. 3. Average turbidity (NTU) across each transect and season. The solid line represents the DOH WQS for the dry season and the dotted line represents the WQS for the wet season.

Table 1
Mean ± standard deviation of ammonia (μmol L^{-1}), dissolved oxygen (DO), nitrate (μmol L^{-1}), phosphate (μmol L^{-1}), salinity, silicate (μmol L^{-1}), temperature (°C) and turbidity (NTU) across seasons and transects.

	Season			Transect		
	Summer 2020	Winter 2020–2021	Summer 2021	North	West	South
Ammonia	<0.09	<0.09	0.31 ± 0.04	<0.09	<0.09	0.25 ± 0.04
DO	5.71 ± 0.05	6.20 ± 0.05	6.14 ± 0.05	5.99 ± 0.06	5.97 ± 0.06	6.09 ± 0.05
Nitrate	0.41 ± 0.10	0.24 ± 0.10	0.16 ± 0.10	0.66 ± 0.10	<0.06	0.15 ± 0.09
Phosphate	<0.01	<0.01	0.04 ± <0.01	0.02 ± <0.01	<0.01	0.02 ± <0.01
Salinity	34.7 ± 0.1	34.5 ± 0.1	34.8 ± 0.1	34.7 ± 0.1	34.6 ± 0.1	34.7 ± 0.1
Silicate	2.16 ± 1.15	7.88 ± 1.13	4.73 ± 1.13	6.95 ± 1.18	4.69 ± 1.16	3.36 ± 1.13
Temperature	26.3 ± 0.3	25.3 ± 0.1	26.3 ± 0.1	25.3 ± 0.1	26.5 ± 0.1	26.1 ± 0.1
Turbidity	0.54 ± 0.06	0.97 ± 0.06	0.78 ± 0.06	1.00 ± 06	0.68 ± 0.06	0.64 ± 0.06

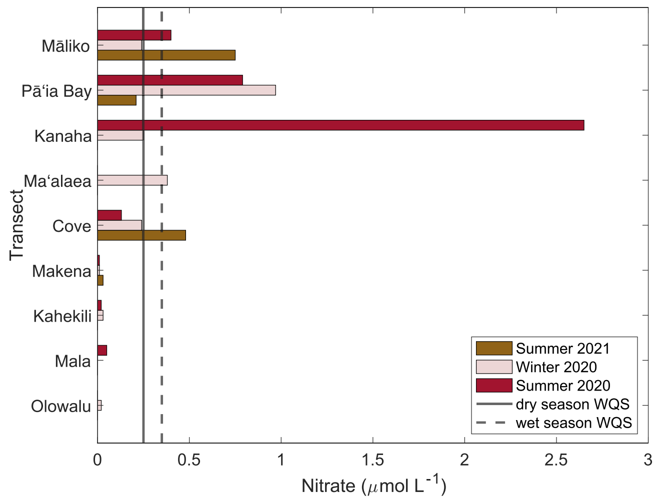

Fig. 4. Average nitrate (μmol L^{-1}) across each transect and season. The solid line represents the DOH WQS for the dry season and the dotted line represents the WQS for the wet season.

the greatest swells during the north shore winter (2.60 ± 0.82 m) and the smallest swells occurring on the south shore, regardless of season (Table 3, Figs. 6 and S1). Summer 2021 wave heights are greater than summer 2020 for north (1.31 ± 0.27 vs 1.05 ± 0.08, respectively) and south shores (0.93 ± 0.13 vs 0.86 ± 0.07, respectively), but the means are not significantly different. Precipitation on the north shore is generally greater than on the south and west sides of Maui Island, although there were no major rain events to generate runoff prior to or during the study sampling periods (Figs. 6, S1). From June 2020 through September 2021 wind speeds were significantly different across all directions and ranged 0.11–16.47 (5.50 ± 2.74) m s^{-1} on the north shore, 0.01–14.34 (2.74 ± 2.42) m s^{-1} on the west shore and 0.03–15.22 (4.06 ± 2.78) m s^{-1} on the south shore (Figs. 6, S1).

4. Discussion

4.1. Spatial trends in water quality

Nitrate and turbidity were consistently higher at Maui's north shore sites relative to the west and south shores (Figs. 3 and 4). The PCA further correlates nitrate and turbidity with high silicate concentrations in the winter (Fig. 5B). Silicate is associated with freshwater sources, including both SGD and surface water (e.g., streams and runoff). Minimal coastal precipitation during the north shore sampling periods rules out major surface water contributions of nitrate and turbidity (Fig. 6). However, previous studies have shown enhanced SGD nitrate flux on Maui's north shore due to fertilizer use for historical sugarcane and pineapple cultivation (Bishop et al., 2017). Tradewinds are generally stronger on the north shore and extratropical storms generate large swells (Fig. 6). These large swells, combined with shoreline erosion, likely source the high turbidity levels at Maliko, Pā'ia Bay and Kanaha, particularly during the winter.

The Hawai'i Coral Reef Assessment and Monitoring Program (CRAMP) has been monitoring reef health across Hawai'i since 1998 (Rodgers et al., 2015). The data from these surveys indicate that sites on Maui's north shore typically have the lowest coral cover, the greatest reduction of percent coral cover over time and the lowest ratios of calcified to fleshy algae. Reduced coral cover and high fleshy algal dominance may be related to increased wave exposure on the north shore in the winter, but high nutrient levels also reduce coral cover and growth, and promote ecosystem shifts from coral to algae-dominated reefs (Friedlander and Dollar, 2008; Gove et al., 2015). The effects of enhanced turbidity and sedimentation on coral reefs include reduced growth rates, calcification, recruitment and net productivity (Rogers, 1990).

The impacts of injection wells on Maui's coastal water quality have been observed at Kahekili, Kanaha, Cove and Ma'alaea (Glenn et al., 2013; Bishop et al., 2017; Miller-Pierce and Rhoads, 2016; Dailer et al., 2010). Treated wastewater released through SGD in coastal environments is characterized by high nutrient concentrations, particularly nitrate, phosphate and ammonia (Swarzenski et al., 2017). In this study, nitrate concentrations exceeded the HI-DOH water quality standards at Kanaha, Cove and Ma'alaea, and may be sourced by SGD containing injected wastewater. Nitrate concentrations at Kahekili Beach Park were comparable to open ocean conditions, potentially due to rapid mixing or

Table 2
PERMANOVA results testing the effects of cardinal direction, season-year, and their interaction on water quality parameters using Euclidean distance and 999 permutations.

Effect	*df*	*SS*	R^2	*F*	*Pr* (>*F*)
Direction	2	6021	0.138	15.093	**0.001**
Season	2	1154	0.026	2.894	**0.016**
Direction:Season	4	2075	0.047	2.601	**0.011**
Residual	173	34,504			
Total	181	43,754			

df = degrees of freedom, *SS* = sum of squares, significant effects ($p < 0.05$) are in bold.

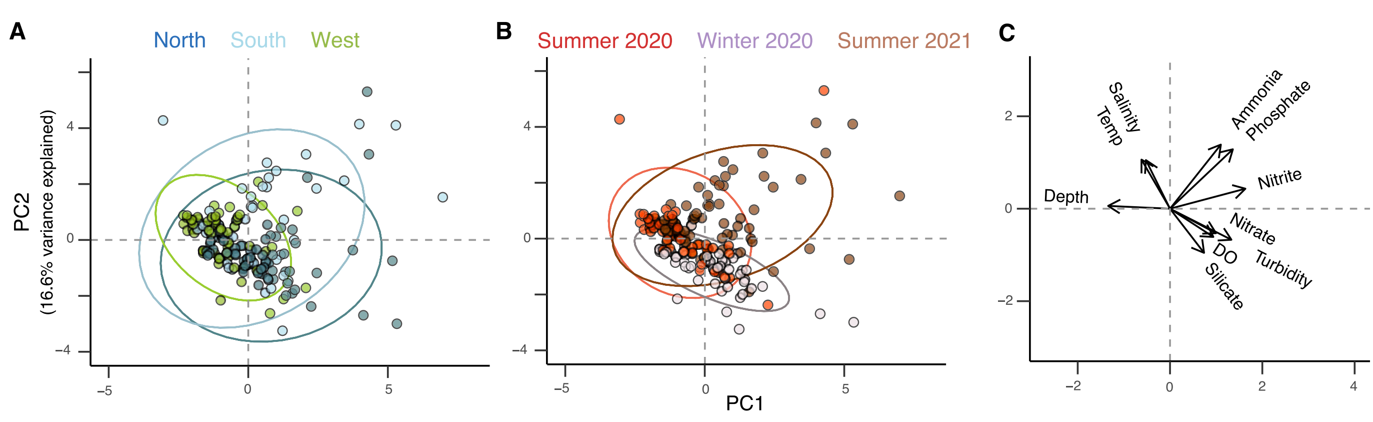

Fig. 5. Principal component analyses (PCA) of water quality parameters in relation to (A) cardinal direction and (B) season-year, (C) with environmental vectors showing significant correlation with PC axes. Variance explained by each PC-axis is in parenthesis. Ellipses represent 95 % standard deviation, and the length of arrows represents the variance of the variables.

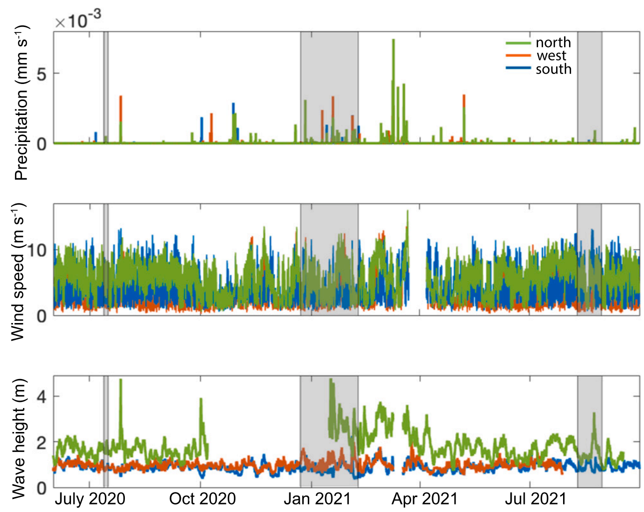

Fig. 6. Precipitation (*top*, mm s^{-1}), wind speeds (*middle*, m s^{-1}) and wave height (*bottom*, m) from June 2020 through September 2021. Colors represent north (*green*), west (*orange*) and south (*blue*). The gray shaded areas are the periods of water quality sampling events. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Wave heights (m, mean ± SD) from buoys measuring north swells (Pauwela, Maui), west swells (Lāna'i) and south swells (Pearl Harbor, O'ahu) in Hawai'i.

	Summer 2020	Winter 2020–2021	Summer 2021
North	1.05 ± 0.08	2.60 ± 0.82	1.31 ± 0.27
West	0.84 ± 0.10	1.47 ± 0.52	NA
South	0.86 ± 0.07	0.82 ± 0.25	0.93 ± 0.13

biological utilization of nutrients.

Degradation of the reef ecosystem at Kahekili Beach Park has been linked to nutrient pollution and coastal acidification associated with injected wastewater from the Lahaina Wastewater Reclamation Facility, and includes reduced coral cover, calcification and diversity, increased dissolution and bioerosion of the reef framework, and algal blooms (Prouty et al., 2017, 2018; Dailer et al., 2010; Smith et al., 2005). In 2012, several community organizations sued Maui County for violating the Clean Water Act since the injected water originates at a point source and is discharged along the coastline of west Maui. In April 2020, the United States Supreme Court ruled that point source pollution entering navigable waters through an indirect route (e.g., groundwater) must comply with environmental requirements under the Clean Water Act (Cornwall, 2020). While this is certainly a positive step forward to improving water quality for coral reefs at Kahekili, the impacts of treated wastewater to coral reefs at Kanaha, Kihei and Ma'alaea remain unknown.

4.2. Temporal trends in water quality

Ammonia and phosphate concentrations were higher at the south shore sites in summer 2021 (Table 1, Fig. 5). As a result of the COVID-related visitor population reduction, the County of Maui Department of Environmental Management (DEM) reports the wastewater reclamation facilities were receiving, treating, and injecting less wastewater during the quarantine (Fig. 2). This may have led to a nutrient reduction in groundwater-wastewater mixtures within the aquifer and subsequently, SGD-receiving coastal waters. Although the residence times of water within aquifers vary across the island, water samples were collected during July 2020, over four months after the implementation of the visitor quarantine and within a reasonable time frame for groundwater-wastewater mixtures to reach the coastline following injection (Glenn et al., 2013).

Nitrate concentrations at Kanaha were greater in summer 2020 relative to summer 2021 (Fig. 4). Kanaha is located adjacent to the Kahului Wastewater Reclamation Facility (KWRF), which is <50 m from the coast. Kahului is an urbanized area of Maui with a high local community population. There are few hotels in the Kahului area and consequently, visitors populate the south and west Maui resort areas. Hence, the visitor population reduction in 2020 had a minimal impact on the amount of wastewater received and injected at the Kahului Wastewater Reclamation Facility (Fig. 2), which injects more nitrogen than the Kihei and Lahaina WRFs combined (Dailer et al., 2010). The stay-at-home orders during COVID may have also increased use of OSDS systems such as cesspools. Cesspools directly discharge wastewater into groundwater, thereby increasing the flux of nitrate into coastal waters (Bishop et al., 2017; Mezzacapo et al., 2020).

Turbidity levels during summer 2021 were higher than in summer 2020 in eight out of nine sites (Fig. 3). High turbidity levels can be driven by precipitation and coastal runoff, or wave activity that resuspends sediment or causes coastal erosion. Wave heights in 2021 were slightly greater on north and south shores during each of the sampling periods, but not significantly different. Therefore, lower turbidity levels in summer 2020 may be related to the visitor quarantine and stay-at-home orders during COVID, which likely reduced road use and traffic (Lund, 2021). In fact, Hawai'i beaches were closed for several periods of time during COVID, limiting local beach use (Currie et al., 2023).

Thermodynamics predict that as temperature and salinity increase, DO concentration declines (Weiss, 1970). Higher nutrient concentrations may increase productivity, which consumes carbon dioxide and increases DO (Nelson and Altieri, 2019). These trends are reflected in the PCA (Fig. 5c), where nitrate and DO are inversely correlated with salinity and temperature. Yet, DO is significantly lower in summer 2020 relative to summer 2021, despite no significant differences in salinity and temperature across sampling periods (Table 1). Further, although average nitrate concentration is greatest in summer 2020, this trend is primarily driven by the elevated nitrate concentrations measured at Kahana on the north shore. The low DO values in summer 2020 may therefore be driven by physical processes, specifically low wave energy, which leads to increased stratification due to lack of mixing and reduced DO in the surface ocean (Wallace and Wirick, 1992; Gajdzik and DeCarlo, 2017) (Table 3).

5. Conclusions

In this study, we report spatial and temporal coastal water quality trends for the island of Maui, Hawai'i. Turbidity and nitrate levels were consistently higher at the north shore sites, which is likely driven by large swells, and nearshore municipal wastewater injection wells and fertilizer use associated with historical agriculture, respectively. Average turbidity across all transects exceeds the DOH WQS, regardless of season. Many sites also exceed the WQS for nitrate, including sites that receive treated wastewater from injection wells.

The COVID visitor quarantine presented a unique and unprecedented opportunity to collect baseline data reflective of a major population reduction on the island of Maui. During this time, nutrient (ammonia and phosphate) concentrations and turbidity levels declined. Although coastal water quality is driven by numerous environmental factors and anthropogenic influences that make the identification of single or multiple drivers challenging, these trends suggest that tourism may play a role in coastal water quality and subsequently, coral reef ecosystem health. Further, the data collected as part of this study serves as an important comparison for future work monitoring water quality, reef health and restoration, and environmental change, including legislative effort to convert Maui cesspools to septic systems by 2050. In addition, in August 2023 Maui experienced severe wildfires in Lahaina and Kula. There are few studies on the impacts of wildfires on coral reefs, particularly urban wildfires, but rural wildfire studies have shown enhanced sedimentation and nutrient loading as post-fires stressors (Prouty et al., 2014; Abram et al., 2003). In the aftermath of these unprecedent wildfires, several groups and organizations have mobilized efforts to assess wildfire impacts on coastal water quality and coral reef communities. Our study offers a unique case where spatiotemporal patterns in coastal water quality were assessed with dramatic changes in wastewater injection. As such, these data will serve as an important baseline for managers and scientists in Hawai'i and across the Pacific region seeking to identify and mitigate the drivers of adverse water quality in coral reef ecosystems.

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CRediT authorship contribution statement

Andrea K. Kealoha: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Christopher B. Wall:** Writing – review & editing, Formal analysis. **Travis A. Liggett:** Writing – review & editing, Data curation.

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Declaration of competing interest

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Data availability

I have shared my data through Mendeley: DOI: 10.17632/kwtg65t7xw.1

Maui Water Quality-Kealoha (Original data) (Mendeley Data)

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