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Marine water quality of a densely populated Pacific atoll (Tarawa, Kiribati): Cumulative pressures and resulting impacts on ecosystem and human health

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ABSTRACT

The resilience of coastal ecosystems and communities to poor environmental and health outcomes is threatened by cumulative anthropogenic pressures. In Kiribati, a developing Pacific Island country where human activities are closely connected with the ocean, both people and environment are particularly vulnerable to coastal pollution. We present a survey of environmental and human health water quality parameters around urban South Tarawa, and an overview of their impacts on the semi-enclosed atoll. Tarawa has significant water quality issues and decisions to guide improvements are hindered by a persistent lack of appropriate and sufficient observations. Our snapshot assessment identifies highest risk locations related to chronic focused and diffuse pollution inputs, and where mixing and dilution with ocean water is restricted. We demonstrate the importance of monitoring in the context of rapidly changing pressures. Our recommendations are relevant to other atoll ecosystems where land-based activities and ocean health are tightly interlinked.

1. Introduction

Marine ecosystems are of global importance (e.g. Milon and Alvarez, 2019), and their ecological health is increasingly threatened by cumulative, largely anthropogenic, pressures of pollutants from land based sources (e.g. Halpern et al., 2008; Hodgson et al., 2019). Terrestrial runoff of waters polluted with nutrients (primarily nitrogen and phosphorus compounds) from point sources, such as sewage, and diffuse sources, such as fertiliser losses, can have devastating effects in lagoon and coastal ecosystems (e.g. Carpenter et al., 1998; Crain et al., 2008; Smith and Schindler, 2009;Morrison and Kaly, 2010; Freeman et al., 2019). Poor water quality puts coastal and lagoon habitats at risk, which directly impacts on coastal communities with a close connection to the marine environment and who depend on these systems to sustain and support economic livelihoods.

The importance of healthy marine environments for healthy communities is recognised in the United Nations Sustainable Development Goals (SDGs, specifically goal 14: Health, the global ocean and marine resources; United Nations, 2015). Within this framework, the advantage of considering the health of the marine ecosystem and people in integrated studies has been highlighted (Wear, 2019). Deterioration of coastal habitats and ecosystem function impacts on many layers of coastal community wellbeing, including societal (WHO, 2003), environmental, and economical (Lee et al., 2020). Sewage, especially in the absence of adequate treatment infrastructure, and agriculture are both sources of bacterial pathogens which impact on people through direct contact or via contaminated seafood (Iwamoto et al., 2010). Poor water quality also decreases the resilience of these systems and can lead to stronger impacts from climate change (Ortiz et al., 2018; Wolff et al., 2018; MacNeil et al., 2019), the threats of which atoll communities are particularly vulnerable to (Barnett and Adger, 2003; Barnett, 2017).

Marine water quality issues are increasingly being measured and reported across Pacific coastal systems (e.g. Brodie et al., 1990; Koshy et al., 2006; Devlin et al., 2020), with atoll islands being particularly

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vulnerable (Morrison and Kaly, 2010; Brodie et al., 2020). Small Island Developing States (SIDS) in the Pacific (as well as the group 'PICTs': Pacific Island Countries and Territories) are characterised by small land mass and large ocean areas. Marine resources dominate their (typically low GDP) economies, with coastal fisheries being particularly important for community well-being (e.g. Gillet, 2016). These remote locations are chronically data-poor (Morrison and Kaly, 2010), and despite the value of the marine environment to Pacific SIDS, their ability to make informed management decisions to protect this resource is greatly hindered by both long term and high spatial resolution data scarcity (Salpin et al., 2018; e.g. Evans et al., 2019). These countries face acute pressures of global-scale environmental changes, in the context of cumulative (negative) impacts from the more local pressures of coastal degradation and poor water quality (e.g. Hay, 2013; Hay et al., 2013; Arikibe and Prasad, 2020; Bakir et al., 2020; Johnson et al., 2020; Pratap et al., 2020). Continuous and long-term monitoring of the coastal and marine environment is required to fully understand the scope and evolution of many of the Pacific pollution issues and to provide the appropriate baseline data for informed prioritisation of mitigation and recovery actions (Borja et al., 2010).

The Republic of Kiribati is the world's largest SIDS in terms of ocean territory, spanning 3.5 million km^2, despite having a land mass of only 811 km^2 (GOK, 2004) and a population of approximately 110,000 (2015 census: KNSO, 2016). Like all Pacific SIDS and more acutely than many due to its limited land area restricted to close proximity to the sea, Kiribati's coastal marine environment faces pressures including increasing population and limited infrastructure and resources to manage pollution (e.g. Jones and Lea, 2007; Storey and Hunter, 2010; Duvat et al., 2013; Mallin, 2018), as well as a well-publicised extreme vulnerability to climate change (Mallin, 2018). Kiribati's administrative and population centre, South Tarawa, is now home to >50% of the county's population; in 1990 Tarawa had a larger population than any other Pacific atoll (Paulay and Kerr, 2001) and it has since more than doubled. Urban South Tarawa has areas of extremely high population density (e.g. in 1995: 1600 people/km^2 in South Tarawa, 5400 people/km^2 in Betio; (Hunt, 1996)), and a steeply rising population (by 12% between the 2010 and 2015 censuses (KNSO, 2016)) despite extremely limited infrastructure. For example, there is no sewage treatment system, and the current sewage outfalls, initially developed in 1993 (Hunt, 1996), were extended off the reef edge and beyond the surf zone to a depth of 30 m and fitted with diffusers only in 2017 (MISE and ADB, 2018). Access to amenities connected to this central sewage system remains an issue, exacerbating the direct input of waste into the lagoon. There is also a shift from traditional subsistence lifestyle towards reliance on imported consumer goods, leading to increased pressure on the atoll's limited waste disposal capacity (Carden, 2003; Redfern, 2006).

A state of the Environment Report (GOK, 2004) outlines the coastal water quality and associated human health issues that are linked to anthropogenic pressures on Kiribati's marine environment, the most pronounced of which are found around South Tarawa. More recently, a year-long monitoring program was carried out which highlighted the pollution issues around the inshore lagoon areas and sites adjacent to the landfill sites (NIWA, 2014a). The extent of South Tarawa's water quality issues has been the focus of a number of national and regional reports (Johannes et al., 1979; Kimmerer and Walsh, 1981; Naidu et al., 1991; Gangaiya, 1994; Abbott et al., 1995; Hunt, 1996, summarised in Supplemental Table 1) and other anthropogenic impacts on Tarawa's marine environment including marine biology (e.g. Zann, 1982; Ebrahim, 2000; Paulay and Kerr, 2001) and coastal erosion (Webb and Kench, 2010; Biribo and Woodroffe, 2013; Duvat, 2013; Duvat et al., 2013) but data from many of these reports are difficult to access and interpret (GOK, 2004). As anthropogenic pressures have evolved, water quality observations have been insufficient in both space and time (Fig. 1); differences between surveys reflect a combination of changing

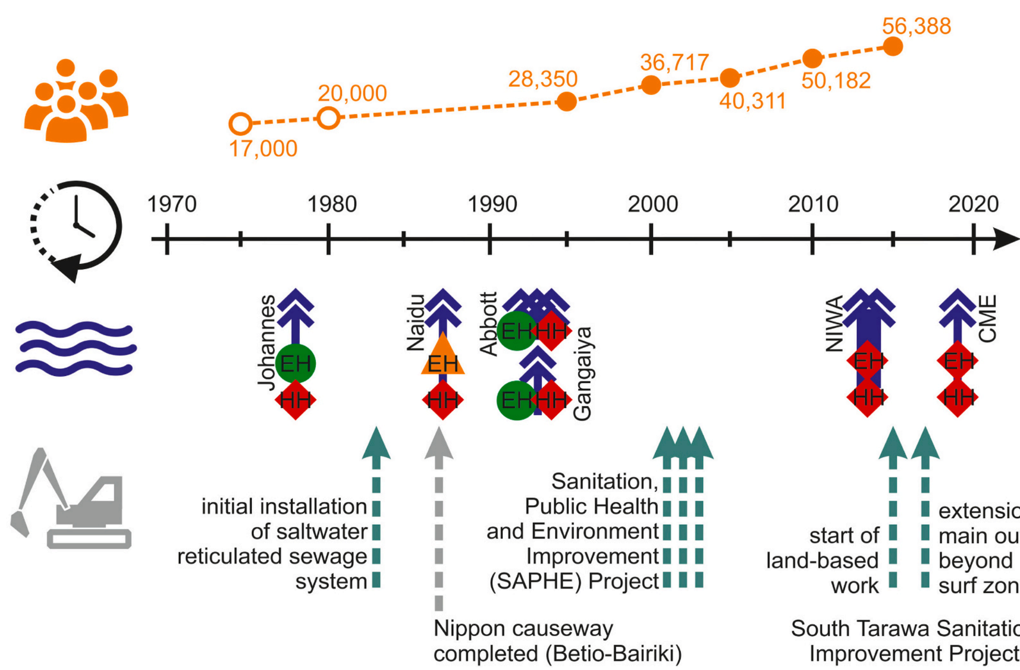

Fig. 1. Comparative timing (black horizontal arrow, years 1970–2020) of population increase (orange circles; number of people); water quality surveys (blue double-headed arrows, with coloured symbols indicating observed risk to ecosystem (E) and human (H) health), and significant South Tarawa infrastructure work (sewerage: green dashed arrows, causeway: grey dashed arrow). Population data are from: Kimmerer and Walsh, 1981; Zann, 1982; KNSO, 2007, 2016, with open circles indicating where the precise year of population was not provided. Water quality survey arrows are labelled by first author surname for: Johannes et al., 1979; Naidu et al., 1991; Gangaiya, 1994; Abbott and Garcia, 1995c; NIWA, 2014a, (see details in Supplemental Table 1, and CME: Commonwealth Marine Economies Programme). Sources for infrastructure dates: Nippon Causeway (Harper, 1988); SAPHE (ADB, 2008, 2011); South Tarawa Sanitation Improvement Project (MISE and ADB, 2018) and project website at: https://www.adb.org/projects/43072-013/main (accessed 10 July 2020). The indicative assignment of level of risk for EH and HH is based on the conclusions of each water quality study, symbol key: green circle: low risk; orange triangle: moderate risk; red diamond: high risk. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

pressures, varying sampling approaches, short-term and small-scale variability, and varied perspectives. Given the importance of the marine environment to the people of Tarawa, and their reliance on coastal ecosystems, it is important to develop and interrogate all available water quality information to provide the data required for rapid and consultative decision-making.

The current work in Kiribati was part of the Commonwealth Marine Economies Programme (HM Government, 2016). It was designed as an initial scoping study to inform development of a monitoring programme for Tarawa, focusing on areas at high risk of water quality issues. Parameters associated with both environmental and human health (Table 1) were included. Though limited to one survey period, observations of this set of parameters considered alongside previous studies provides an indicative integrated assessment with relevance to both environmental and socio-economic factors which will help inform ongoing efforts towards sustainable environmental management. By putting our survey in the context of earlier water quality monitoring efforts and known increasing anthropogenic pressures, we highlight key considerations that future monitoring must address to ensure it provides an accurate understanding of the level of risk from poor water quality.

2. Methods

2.1. Sampling design

Tarawa is a triangular atoll with a submerged western edge. The western edge is largely at several meters and up to 9 m water depth, except for the deep (20 m (Damlamian, 2008)) shipping channel near Betio in the south (Paulay and Kerr, 2001). A road runs the length of South Tarawa, connecting Betio (and the main port) in the west to Bonriki and Tanaea (and the airport) in the east. The road includes several causeways, the longest of which is between Betio and Bairiki and has a central bridge to allow a fisheries access channel for smaller boats. The islands of North Tarawa, from Buota in the south east to Buariki in the north west, remain rural and are less easily accessed and less populated.

While most central Pacific atolls lie in oligotrophic gyres, Tarawa is in the nutrient-rich waters of the equatorial upwelling zone (Paulay and

Table 1
Details of water quality parameters surveyed as part of the 2019 CME Programme. References are provided as sources of further information.

Category	Parameter	Description	For more detail, see:
Physical	Water temperature Water salinity	• Provides the context for water circulation which serves to disperse contamination away from inputs and mix (dilute) highly polluted with less polluted waters. • Related to seasonal and inter-annual rainfall patterns and anthropogenic changes in lagoon circulation (i.e. building causeways).	For Tarawa: Kimmerer and Walsh, 1981; Abbott and Garcia, 1995c; Damlamian, 2008
Ecosystem Health	Dissolved and particulate nutrients	• Necessary for marine primary production (e.g. phytoplankton growth). • Released to the marine environment above natural concentrations in human waste and by human activities (agriculture, aquaculture). • High concentrations lead to large phytoplankton blooms.	Eutrophication review: Smith and Schindler, 2009
	Chlorophyll	• Measure of phytoplankton abundance.	
	Turbidity/Suspended Solids	• Particulate load in the water column, which acts to restrict light penetration impeding deeper photosynthetic life (e.g. seagrass). • Increased by plankton blooms, and coastal modification which increases availability of loose sediments.	
	Dissolved oxygen	• Surface water is re-supplied with oxygen from the overlying atmosphere. • Primary production increases oxygen concentrations, while (aerobic) breakdown of organic matter (remineralisation) in the water column depletes oxygen. • Low oxygen concentrations are considered harmful to marine life.	
Human Health	*Escherichia coli* (*E. coli*)	• Coliform bacterium excreted in the faeces of humans and other warm-blooded organisms. • Faecal-oral transmission of pathogenic strains cause disease including gastroenteritis, urinary tract infections and neonatal meningitis. • Cells survive for only a limited time in the environment and are therefore often used as an indicator of recent faecal contamination.	WHO, 2003
	Intestinal enterococci	• Bacterium excreted in the faeces of humans and other warm-blooded organisms. • Abundance of cells used for international bathing water quality standards because of longer survival time in the marine environment compared to *E. coli*.	
	Antimicrobial resistance (AMR)	• Increasing resistance to common antibiotics used in the treatment of human disease is a high-priority global public health concern, and has been highlighted as particularly acute in Pacific Island Countries and Territories. • Extended spectrum beta-lactamase (ESBL) - producing bacteria are resistant to third and fourth generation cephalosporins, an important class of antibiotics. • ESBL-producing bacteria have limited treatment options and are often associated with hospital-acquired infections. • ESBLs are associated with many faecal bacteria including several pathogens, e.g. *Salmonella enterica*, *E. coli* and *Klebsiella pneumoniae*.	Le Quesne et al., 2018; Collis et al., 2019; Foxlee et al., 2019; Loftus et al., 2020
	Vibrio	• Genus of bacteria several species of which cause foodborne infection particularly from undercooked seafood and contaminated drinking water. • Pathogenic strains are associated with gastroenteritis and infection of open wounds causing septicaemia (blood poisoning). • Occur naturally in the marine environment and are carried by numerous marine animals. Their abundance is not comparable to traditionally used faecal indicators except in waters receiving human waste from disease outbreaks (mainly cholera). Incidence/risk of disease in people bathing in the marine environment, for *Vibrio cholerae* require abundances 10^6. Infectious doses of other Vibrio species causing extraintestinal infections, especially ear and wound infections are unknown. Outbreaks of Vibrio-related disease are increasing, and their provenance have been linked to rising ocean temperatures.	WHO, 2003; Horwood and Greenhi, 2016; Baker-Austin et al., 2018

Kerr, 2001). Its position close to the equator is outside the impact of tropical cyclones. The tidal range is more than 2 m (spring tides 2.4 m and neap tides 0.5 m Damlamian and Webb, 2008), with inter-annual variability linked to the Southern Oscillation Index (La Niña and El Niño conditions) (Biribo and Woodroffe, 2013) and predominant wind and ocean wave direction from the west. The water depth in the lagoon is 5–20 m (Paulay and Kerr, 2001).

Water samples and *in situ* measurements were made both from shore, and from land using a small, motorised boat in Tarawa lagoon and the ocean side of South Tarawa from 2 to 11 March 2019. Survey design aimed to provide a snapshot spatial overview of a range of water quality parameters, but also to focus on South Tawara sites known to be heavily impacted by human activities. Existing information from an earlier water quality survey (NIWA, 2014a) as well as information on the most densely populated areas, was used to guide site selection. For reporting, sampling sites have been divided into 12 site groupings subject to similar key pressures, described in Table 2 and shown in Fig. 2.

2.2. Sampling methods

An RBR Maestro[3] (RBR Ltd. Ottawa, Canada) was used to make in situ measurements of temperature, salinity, turbidity, chlorophyll (fluorescence) and dissolved oxygen concentration. The instrument was equipped with the following sensors: RBR Marine CT (conductivity-temperature); Seapoint STM Turbidity, and chlorophyll fluorometer (Seapoint Sensors Inc., USA); RBRcodaODO|fast8 oxygen optode. Depth profiles through the water column were obtained where the total depth was greater than approximately 1 m. Profile data (downcast) was processed using RSKtools for matlab (v3.4.0) including bin averaging to 0.1 hPa, and smoothing using the 'boxcar' method with a window length of 3. Near surface data were extracted. Total water depth was estimated using Deeper Smart Sonar PRO+ (Vilnius, Lithuania). Additional sensor measurements were made on the sampled water immediately prior to subsampling using a handheld multi-parameter portable meter (WTW MultiLine Multi 3630 IDS, Xylem Analytics, Germany).

Oxygen concentrations have been corrected based on in-air measurements from throughout the survey (following (Bittig et al., 2018)) using in-air concentrations calculated from the nearest European Centre for Medium-Range Weather Forecasts (EMCWF) Copernicus Atmosphere Monitoring Service (CAMS) near real time atmospheric data (https://apps.ecmwf.int/datasets/data/cams-nrealtime/); for which air-temperature agreed with RBR measurements within 1 °C, (mean difference 0.2 °C). The resulting estimated accuracy is better than ±5%. Chlorophyll sensor data are presented as raw fluorometer output and should be interpreted as relative rather than absolute measurements: it was not appropriate to use our surface water samples for calibration given the evidence for small-scale variability with depth and different near-surface depths sampled by the two methods. Turbidity measurements are reported as per the factory calibration.

Water samples were collected for total and dissolved nutrients, total suspended solids (TSS) and pigments (chlorophyll-a and phaeophytin), analysed at the Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER), Australia. Dissolved nutrients were collected through a 0.45 μm syringe-tip polyethersulfone (PES) membrane filter. Nutrient samples were immediately stored on ice, and then frozen until analysis. Concentrations were determined using standard procedures (Ryle and Wellington, 1982) with a Skalar San++ continuous flow analyser (Skalar Analytical, Breda, The Netherlands). Detection limits were 0.006 mg/L for ammonia, 0.01 mg/L for nitrate + nitrite and 0.01 μg/L for dissolved inorganic phosphorous (filterable reactive phosphorous). Artificial seawater was used to establish baseline characteristics. Analyses of the total dissolved nutrients (total dissolved nitrogen and total dissolved phosphate) were carried out using persulfate digestion of the water samples (Valderrama, 1981) and samples were then analysed for inorganic nutrients, as above.

Pigment samples were collected into dark plastic bottles and stored on ice until vacuum filtration of 100 mL onto 47 mm GF/F 0.45 μm glass microfibre filters at the end of each sampling day. Filters were stored frozen until determination of pigment concentration (chlorophyll-a and phaeophytin) by fluorometric technique, following maceration of algal cells and extraction in acetone (Parsons, 2013). A Turner 10-005R fluorometer was used for the analysis and was periodically calibrated using extracts prepared from log-phase diatom cultures (Jeffrey and Humphrey, 1975). Water for determination of TSS was collected in clear plastic bottles, and up to 1 L was filtered onto pre-weighed filters glass microfiber filters (934-AH RTU, GE Healthcare Whatman), dried and stored at room temperature until gravimetric analysis following at least 12 h in the oven at 60 °C.

Samples for microbiological analyses were collected directly into sterile pots and transported to Cefas' field laboratory in insulated boxes on ice. All samples were analysed on day of collection. Three different subsample volumes or dilutions were used to achieve countable colonies (>300) using membrane filtration apparatus Wagtech™ Potatest 2 (Palintest, UK). The following microbiological media and incubation temperatures were used to target *Escherichia coli* (*E. coli*), intestinal enterococci, total *Vibrio* sp., and extended spectrum beta-lactamase (ESBL) producing bacteria. Nutrient pads were used to identify *E. coli* (ECD NPS & gridded MF, 0.45 μm) and intestinal enterococci (Azide NPS & gridded Mf, 0.45 μm). These were rehydrated with > 5 mL of sterile water, then the filtered sample membrane was added prior to incubation at 37 ± 1 °C for 24 h. Filtered membranes were added directly to sterile TCBS Cholera medium (Oxoid, PO0194) and Brilliance ESBL medium (AGAR Oxoid PO5302) and incubated at 37 ± 1 °C for 24 h. Colonies were counted according to colour and morphology in Cefas' field laboratory following incubation. The colony identification is based on the selective agar screen only and should therefore be regarded as presumptive as per the manufacturer's specification. Final colony concentrations per 100 mL (reported as colony forming units: cfu/100 mL) were calculated according to volume and dilution factor. Methodology was according to the Standing Committee of Analysists Microbiology of Recreational and Environmental Waters (2015, 2016a, 2016b).

2.3. Assessment

In order to identify high risk sites of priority for future management actions, we compare our observations to relevant assessment guidelines.

2.3.1. Eutrophication

In the absence of regional or national water quality guidelines or threshold values, we have adapted the use of 'default guideline values' (DGGVs) from the Australian and New Zealand guidelines for fresh and marine water quality (ANZECC and ARMCANZ, 2000; ANZG, 2018) to identify level of concern. Exceedance for any parameter indicates a possible eutrophication issue and considering multiple parameters provides a rudimentary water quality assessment as part of a weight of evidence approach. DVGs for key parameters are listed in Table 3, alongside maximum values from earliest available water quality dataset for Tarawa Lagoon (Johannes et al., 1979; Kimmerer and Walsh, 1981) which are below or close to the guidelines.

2.3.2. Risk to human health

The World Health Organisation's *Guidelines for Safe Recreation Water Environments* (Volume I: Fresh and Coastal Waters) (WHO, 2003) provide a basis for development of international and national approaches and a framework for local decision-making with relevance to the public health risks of faecal contamination in coastal waters. Guideline values are based on calculation of a 95th percentile intestinal enterococci abundance value (derived from at least 60 samples over a 3-year period) corresponding to levels of risk based on exposure conditions and the dose-response relationship with both gastrointestinal illness (GI) and acute febrile respiratory illness (AFRI).

Classification of a water environment also includes a "sanitary inspection of the beach and water catchment" identifying and assessing the sources of faecal contamination such as direct and indirect sewerage inputs (WHO, 2003). Recent sewerage outfall development in South Tarawa imply that the 'sanitary inspection category', or susceptibility to faecal influence, of coastal waters should have decreased but given the lack of sewerage treatment and history of direct faecal inputs (including from septic tanks) a categorisation of 'high' to 'very high' is likely still applicable in populated areas, while 'low' to 'moderate' may be appropriate away from inputs, e.g. off causeways.

The WHO classification (assessment) procedure is clearly not intended for application to single-survey or single-sample observations such as are presented in the current data set. However, in the absence of appropriate data from which to derive a 95th percentile value, we apply these abundance thresholds associated with the classification guidelines to provide context for the level of contamination observed in March 2019. These are intestinal enterococci abundance values, in cfu/100 mL of: ≤40 (A), 41–200 (B), 201–500 (C), >500 (D) (WHO, 2003). Where classification "A" corresponds to an estimated risk per exposure (for a healthy adult) of <1% for GI and <0.3% for AFRI and the respective risks at D are >10% and >3.9%. In combination with a 'sanity inspection categorisation' of 'very high' (densely populated areas) these would correspond to assessment of the water environment of 'follow up' (A), 'Fair' (B), 'Poor' (C) and 'Very Poor' (D).

3. Results

The full survey data set is available for download from the Cefas Data Hub (http://data.cefas.co.uk/#/View/20538; Graves et al., 2020).

3.1. Physical description (salinity and temperature)

Surface water temperature ranged from 27.9 to 33.8 °C, and salinity from 30.9 to 35.05 (Fig. 3). Water temperature broadly decreased with salinity, with highest temperatures and salinities observed at shallow ocean sites sampled near low-tide in the mid-day sun (Fig. 3a, group 'Ocean Shore' sites; and Fig. 3d 'Hospital' sites). Salinity in the lagoon decreased away from ocean influence, indicating that freshwater inputs exceed evaporation (Fig. 3c). The heaviest daily rainfall (190 mm) recorded for three years (the period for which the Tarawa synoptic weather observations include near-complete data), occurred during sampling, with 2019 being a wet year (2017–2019 rainfall are shown in Supplemental Fig. 1). This is supported by the presence of a thin shallow fresher, and colder, layer evidenced by lower salinities of handheld sensor measurements of sampled water compared to near-surface salinity from the profiling sensors. The profiling sensor 'surface' data (Fig. 3) sampled at a minimum depth of approx. 50 cm, while the handled sensor (data not shown) measured at ≤ 50 cm water depth and observed consistently lower salinity, on average 0.3 psu, maximum 4 psu. Some sites close to the reef edge on the ocean side of South Tarawa, sampled near low tide at total water depth of approximately 8 m, had reduced salinities of 34.1–34.3 overlying more oceanic water (Fig. 4, sites 16–21). Below the top ~ 0.5 m lagoon water was typically well-mixed, and the water quality parameters measured in near-surface water samples should therefore typify the full water column (profiles not shown).

Table 2
Summarised description of site groupings. Not all parameters were measured at all sites. Tide information extracted from NOAA/NOS/CO-OPS Tide Predictions for Tarawa Atoll, downloaded April 2019, datum: MLLW (Mean Lower Low Water). 'Boat' samples were taken from a small motorised boat, generally (except in central lagoon) at the closest possible approach to land, while 'Shore' samples were collected from land and therefore closer to onshore pollutant sources.

Site group name	Number of sites	Sample type	Date(s) sampled (as dd/03/2019)	Tidal state (specific site IDs) [height range, m]	Description of local environment/pressures (specific site ID numbers within group)
North Tarawa	7	Boat	11	Falling to rising. [−0.1 to 0.5]	Relatively rural area, sites selected near villages.
Central Lagoon	9	Boat	9, 11	Varied. [−0.1 to 1.1]	Differs between sites: main shipping entrance to Lagoon (36, 37); Betio causeway bridge (41); sandbars including near boat wreckage (42–44); away from local pressures (48,49,57).
Ocean	7	Boat	7, 9	Varied. [−0.3 to 1.24]	Differs between sites: Betio (16) and Bairiki (17) sewage outflows; main shipping entrance to lagoon (2, 35).
Ocean shore	4	Shore	2, 5, 11	Falling, near high (5,8) Rising, low-mid (14, 58) [0.7–1.8]	Differs between sites: off causeways further from expected direct anthropogenic inputs (5, 8); above thick seagrass bed off causeway (14); off densely populated area sampled in poorly mixed low-tide pooling water (58).
Hospital (Nawerewere)	3	Shore	8, 10	Rising, near high (30) Rising, near low (46, 47) [−0.14 to 1.64]	Tungaru Central Hospital site complex located adjacent to ocean shore. One of South Tarawa's three sewage outfalls is installed adjacent to the hospital, at only about 2 km from separate outfall serving the hospital itself. Sites were sampled at furthest offshore shore-accessible point at high tide (30), and approximately 150 m further offshore at low tide (45). Site 47 is approx. 800 m to the west, down shore from hospital.
Southern Lagoon	6	Boat and Shore	2, 8, 9	Low, except 1 high (6) [−0.2 to 1.8]	Shore off causeway away from direct pressures sampled at high tide (6), and boat sites near South Tarawa beyond low-tide mark.
Betio	4	Boat	9	Near high, falling. [1.5 to 1.8]	Highest population density. Adjacent to hospital and landfill. Sampling sites lie below low-water line (> 60 m offshore from beach).
Port	3	Shore and Boat	3, 9	High (11) mid (38) low (45) [−0.22 to 1.9]	Inner port (45) has limited circulation and several boats moored. Scrap metal dump sites nearby. Outer port better mixed (11) but subject to high boat traffic: fishing and recreational swimming observed. Larger ships dock and anchor in lagoon outside port (38)
Landfill (Nanikai /Anderson)	6	Shore and Boat	2, 3, 7, 8	Varied. [0.07 to 1.86]	One of island's three main landfills, on lagoon foreshore (Anderson causeway) contained by a low seawall (dry at low tide) and high chain-link fencing. Immediate vicinity sampled from landfill wall (9,10) and near low tide point approx. 150 m away at high tide (60). Remaining sites all within 1 km of landfill.
Inner Lagoon	3	Boat	8	Near low. [0.3 to −0.2]	Lagoon area furthest from main exchange of water with the ocean, and near milkfish ponds. Bikenibeu landfill and generator site is located to the south (24, at 300 m distance).
Milkfish Ponds (Temaiku)	6	Shore	2, 4, 7, 10	Varied. [0.2 to 1.7 m]	Sites near and in channel connecting milkfish (*Chanos chanos*) aquaculture ponds to inner lagoon.
Buota Bridge	3	Shore	2, 6	Falling, near low (1, 2) Rising, near high (15) [0.3 to 1.4]	Channel connecting inner lagoon to open ocean water. Near end of road connecting South Tarawa, relatively rural. Fishing and swimming observed. Turbid plume observed discharging from land near base of bridge (15).

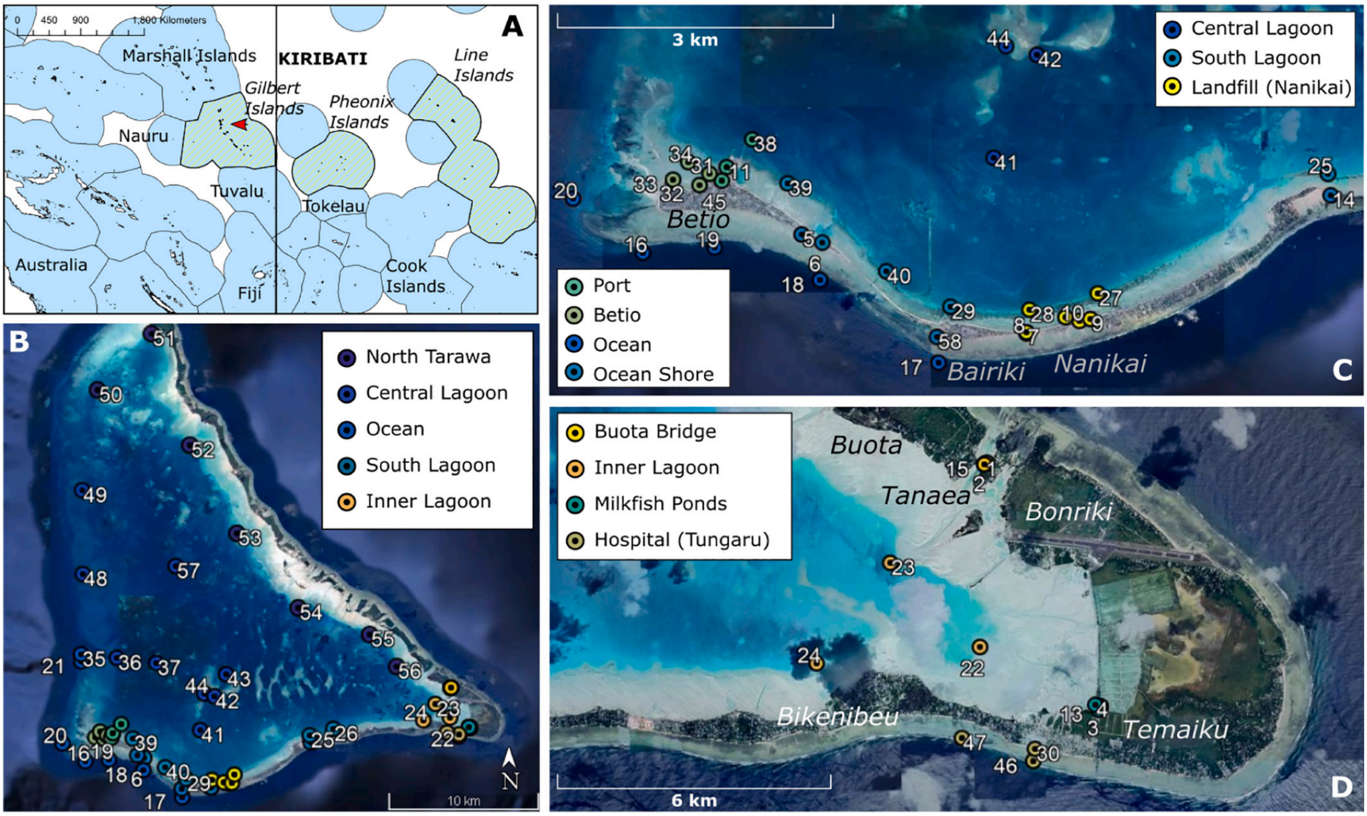

Fig. 2. A Kiribati Exclusive Economic Zone (EEZ, in green), with location of Tarawa shown by red arrow, vertical black line is 180° longitude. B–C: Location of sampling sites (numbered circles) and site groupings (given by circle colours as indicated in legends), alongside island/village names mentioned in the text shown in *italicised* font. Note that the Nanikai landfill is located on the Anderson causeway and sometimes known by that name, and that the milkfish ponds extend north of the sites sampled as seen shown in the map image. A based on marine boundaries of (Flanders Marine Institute, 2019), B–C produced using Google Earth Pro; image information: Data SIO, NOAA, U.S. Navy, NGA, GEBCO; Image © 2020 Maxar Technologies; Data LDEO-Columbia, NSF, NOAA; Image © CNES/Airbus. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Eutrophication parameters

Concentrations of parameters associated with eutrophication assessment (nutrients, pigments, turbidity and dissolved oxygen) are summarised by site grouping in Fig. 5. There was weak negative correlation with salinity for some parameters (see Supplemental Figures and subsequent paragraphs), but proximity to land-based sources of nutrients appears to dominate distribution patterns between and within site groupings. North Tarawa lagoon sites had lowest average concentrations of total nitrogen and phosphorous, nitrate, nitrite, and ammonia, and average chlorophyll below the indicative assessment threshold and near-saturation dissolved oxygen. However, average concentrations of dissolved nutrient species for all site groupings exceeded the assessment thresholds, with nitrate, phosphate and ammonia concentrations being more than an order of magnitude above those observed in the lagoon in 1978 (Johannes et al., 1979; Kimmerer and Walsh, 1981).

Table 3
Default guideline values (DVGs) for available eutrophication parameters, as recommended for tropical Australian slightly disturbed marine inshore ecosystems with clear waters (Tables 3.3.4 and 3.3.5 in (ANZECC and ARMCANZ, 2000), oxygen values are for estuarine waters), compared to the maximum values observed in the lagoon from a 1978 survey as reported in Johannes et al. (1979) and Kimmerer and Walsh (1981).

Parameter (unit)	Default guideline value (DGV)	Tarawa lagoon maximum in 1978
NO_x (μg N/L)	2	2.6
Ammonia (μg N/L)	1	0.36
Total nitrogen (μg N/L)	100	–
Phosphate (FRP; μg P/L)	5	0.33
total phosphorous (μg P/L)	15	–
chlorophyll-a (mg/L)	0.7	0.96
Turbidity (NTU)	20	–
Dissolved oxygen (% saturation)	<80 and >120	Approx. 100

Nitrite and ammonia were near detection limit at nearly all sites, with the exceptions being the Nanikai landfill, the hospital (high nitrate), and the milkfish ponds (high ammonia). Highest ammonia concentrations occur in the lowest salinity samples ($S<33$), and there was a significant negative correlation between salinity and ammonia concentration across all sites sampled, though within some site groupings this relationship is reversed Supplemental Fig. 2. Dissolved inorganic nitrogen and particulate nitrogen were both present at relatively constant concentrations across the majority of sites (50–85 μg-N/L and <50 μg-N/L, respectively at 70% of sites), but elevated in the port, near the milkfish ponds and in some low-tide ocean shore samples (see upper left-hand panel in Fig. 5). There is a significant negative correlation between particulate nitrogen and salinity, which is strongest within the lagoon Supplemental Fig. 3.

There is a similar distribution of dissolved inorganic (DIP), organic, and particulate phosphate (P) species in terms of sites with highest concentration. Ocean water is phosphate-limited (mean DIN:DIP 50), but all site groupings showed some significant phosphate with minimum DIN:DIP of 1–8.5: highest at the milkfish ponds (see lower left-hand panel in Fig. 5). Both dissolved organic and particulate phosphate were significantly correlated with salinity within the lagoon (Supplemental Fig. 4).

Phytoplankton pigments (chlorophyll and pheophytin) concentrations were very low in ocean samples, increasing in North Tarawa and central lagoon waters (see Supplemental Fig. 5). Chlorophyll was elevated and exceeded both the chosen assessment threshold (0.7 μg/L) and the historical maximum value (0.9 μg/L: Kimmerer and Walsh (1981)), at the milkfish ponds, inner lagoon, landfill, and port. More oceanic waters had lowest pigment concentrations, while fresher waters within the lagoon had highest concentrations depth profiles indicate that shallow lagoon waters are typically well-mixed, though increases of chlorophyll fluorescence with depth were observed at some deeper central lagoon sites. Where temperature-salinity stratification was present inside the Betio port and off Betio at the reef edge (for example, site 20 in Fig. 4), subsurface chlorophyll maxima were observed.

Waters around Tarawa generally appeared clear, particularly in the central lagoon and near North Tarawa. Nearly all turbidity readings were below the assessment threshold of 20 NTU (Fig. 4). Higher TSS values occurred closer to human disturbances around South Tarawa, most significantly in shallow stagnant low-tide ocean-side waters (site group 'Ocean Shore') and the rapidly flowing milkfish pond outflow, which were also high in dissolved and particulate nutrients and chlorophyll.

Most sites were close to 100% oxygen saturated (31/55, or 65% of sites between 90 and 110% saturation), with 50% of sites having surface-water dissolved oxygen concentrations between 6 and 7 mg/L. However, we observed occurrences of both oxygen supersaturation (up to 150%), associated with high primary productivity and oxygen production in the water column (landfill and hospital sites at low tide), and oxygen depletion (down to 55% saturation) associated with the oxygen utilisation for the breakdown of high loads of organic material (inner port, Betio, and milkfish pond sites). The low-oxygen water observed off Betio in the lagoon was also present on the ocean side near the reef-edge (Fig. 4).

Repeated sampling near the milkfish ponds in the inner lagoon provides an example of the short-term temporal variability of eutrophication parameters within a small area, which can be related back to physical controls (Fig. 6). Our initial sample at low tide (+ 0.2 m tidal height) had the most significant oxygen depletion (3.6 mg/L; 55% saturation), and highest concentrations of several nutrients, for example ammonia (1.5 times the relevant indicative threshold of 15 μg-N/L; (ANZECC and ARMCANZ, 2000)). The impact of heavy rainfall, flushing nutrient-rich waters from the aquaculture area while simultaneously diluting surface waters is seen in a near-low (rising) tide (+0.28 m) sample where salinity was reduced by 1.1 psu. Near high tide (falling) the water properties were very similar to those found in the inner lagoon at low tide, though an increased oxygen depletion (to 78% saturation) is already observed.

3.3. Microbiological parameters

Microbiological human health risk marker abundances at all sampling sites are summarised in Fig. 7, and shown for all sites in Supplemental Fig. 6. The general picture is varied, reflecting intermittent and spatially heterogenous abundance patterns. The presence of faecal bacteria was widespread, with presumptive intestinal enterococci, the longer-lived environmental marker, detected at all but four sampling sites. Where both intestinal enterococci and *E. coli* were present, there was a significant correlation between presumptive *E. coli* and enterococci abundance (Pearson *p*-value for log(x+1) transformed data: 4×10^{-6}; Supplemental Fig. 7).

Just under half of the samples in which were intestinal enterococci were enumerated (n=19 of 40), mostly located in the lagoon further from the shore, fall in the lowest -risk microbiological water quality assessment. A quarter of samples fall into the two upper-most categories, implying a significant risk to health for anyone exposed to these waters. The maximum observed presumptive intestinal enterococci abundance of 3.9×10^3 cfu/100 mL, observed near the Tungaru Central Hospital sewage outfall pipe (site 30, see location in Fig. 2), is of the same order of magnitude of the lower range of values expected for raw sewage (4.7×10^3 - 4×10^5 (WHO, 2003)).

The highest abundance of ESBL-producing bacteria, by 2 orders of magnitude (1790 cfu/100 mL), was observed near the Tungaru Central Hospital outfall at low tide. The second highest observed abundance was at the same site at high tide (32 cfu/100 mL). The area impacted is likely to be relatively localised: no ESBL-producing bacteria were detected at a site approximately 800 m down-shore sampled at the same time as the highest abundance was observed. The samples from closest to the Betio hospital, obtained at high tide slightly offshore of the low-tide mark, had a much lower ESBL abundance of 1–4 cfu/100 mL.

Presumptive *Vibrio* spp. were isolated from all but 3 sites and was significantly more abundant than other microbiological parameters away from direct sites of high human impact, with a mean reef-edge ocean abundance of 1400 cfu/100 mL. At impacted sites, abundance was both comparatively low (landfill and port sites) and comparatively high (milkfish ponds, Betio, and Tungaru Central Hospital sites).

4. Discussion

4.1. High risk areas

This survey provides a snapshot overview of water quality around

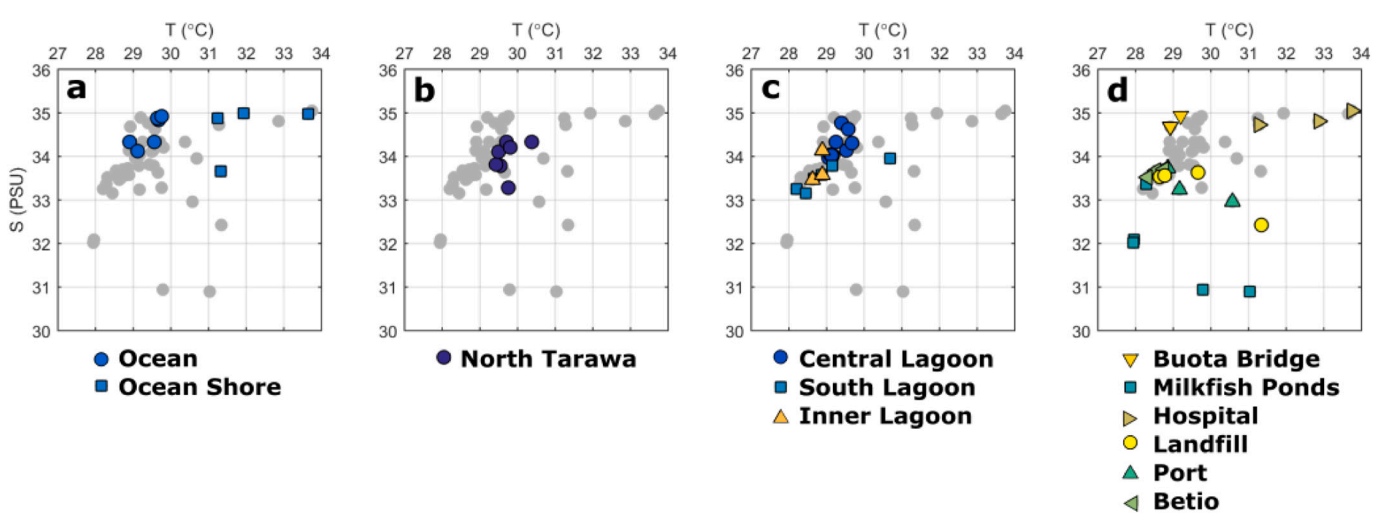

Fig. 3. Temperature and salinity of near-surface water (depth approximately 0.5 m) for all sampled sites. Grey circles: all samples (constant across a–d) symbol colour and shape indicates site grouping (defined in Fig. 2 and Table 2) as indicated in legends. Site groupings have been divided between sub-plots to avoid excessive overlap and their demonstrate differences and similarities.

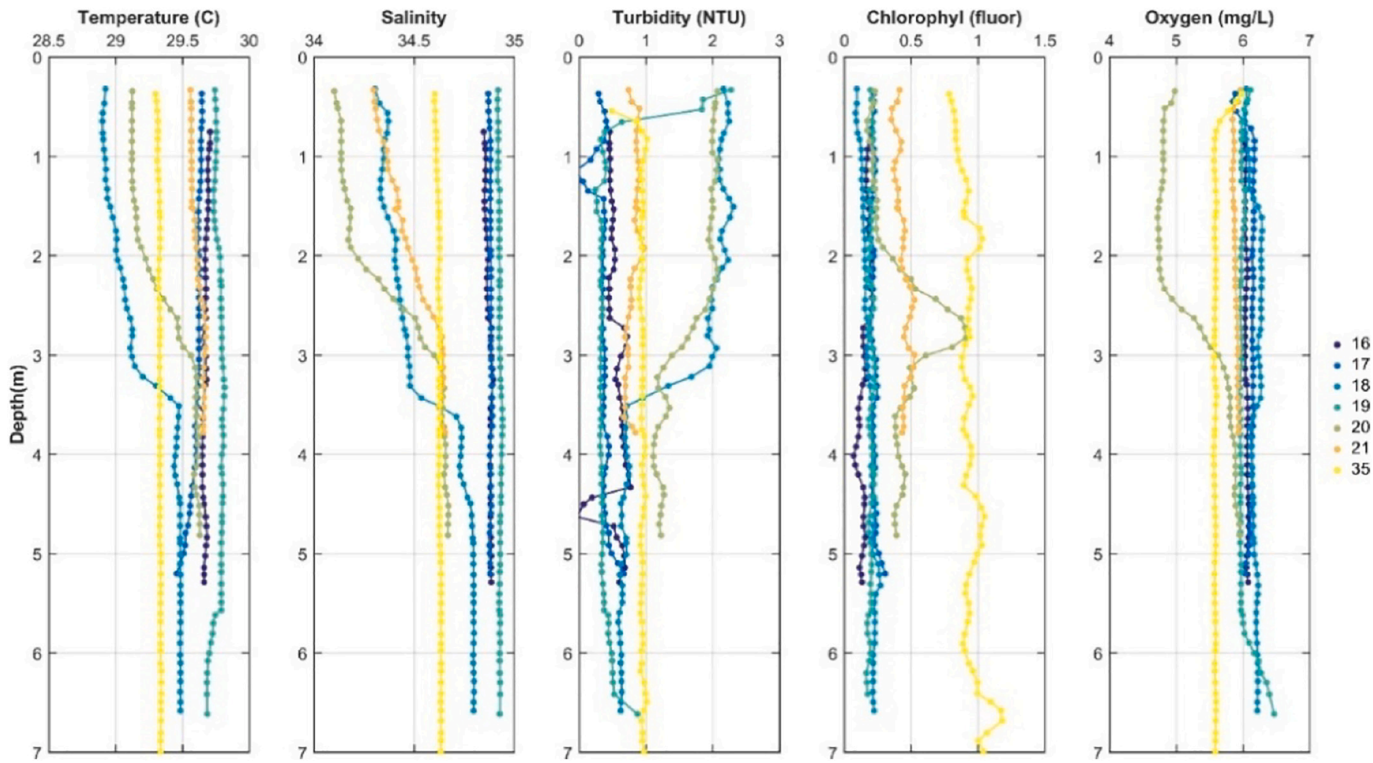

Fig. 4. Depth profiles for ocean sites. Sites 16–21 were sampled close to the reef edge near low tide (tidal height −0.3 to +0.3 m) on 7/03/2019, while site 35 (yellow) was sampled 9/03/2019 on the falling tide (height 1.24 m). Sites 35 and 21 (orange) are co-located in the shipping channel. Profiles do not extend to the seafloor, which was estimated to be at approximately 40–55 m (sites 16 and 17) to 8–12 m total water depth. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

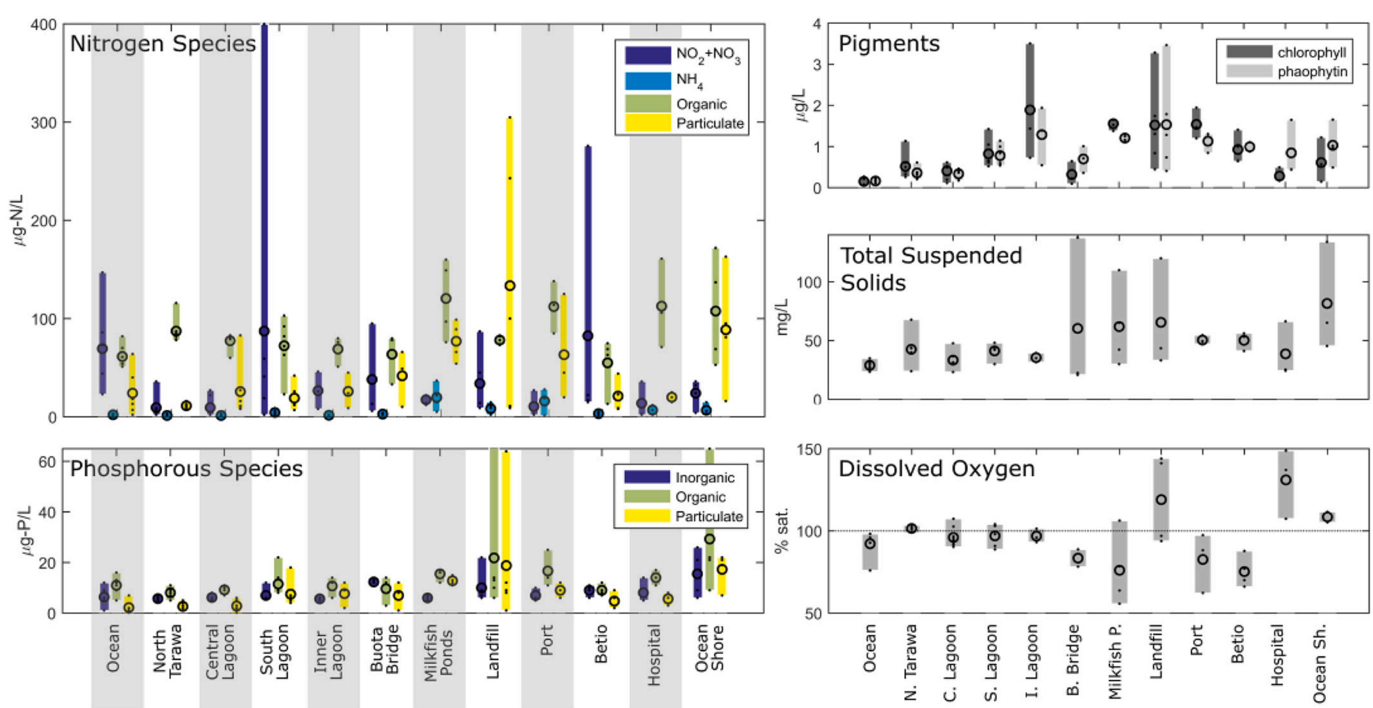

Fig. 5. Summary of eutrophication parameter concentrations by site group (see Fig. 2 for site grouping locations). Bars show range of values observed at sites within that group (minimum to maximum), large open circles arithmetic mean, and small black points individual observations. The number of sites sampled in each site group is given in Table 2.

Tarawa in terms of both environmental and human health status, including measurements of microbiological markers not previously determined in Kiribati. Coastal ocean and lagoon waters around South Tarawa are negatively impacted by direct and diffuse inputs of anthropogenic waste, putting both ecosystem and human health at risk. The most severely impacted areas (as mapped in Fig. 8) are associated with hospital waste, aquacultural nutrient inputs and reduced circulation, and heavy human activity near sewage outfalls, landfill, and the Betio port. These areas differ in the severity of risk to human compared to environmental health as well as in the most significant pressures on the system and local flushing and mixing.

A series of significant improvements in the sewage infrastructure have been undertaken since the water quality survey of Kimmerer and Walsh (1981) due to ongoing and increasing concerns of pollution impacts (see Fig. 1 for timeline summary). However, between improvement projects, the system has gone through periods of disrepair and continues to face increasing pressure from rapid population growth (e.g.: ADB, 2008, 2011; MISE and ADB, 2018). In the past, leaks from the sewage pipes extending off the reef has been a significant issue (MPWU, 2015), and likely impacted the outcomes of previous assessments (NIWA, 2014a). Before the most recent rehabilitation of the infrastructure in 2017, the state of the system was described as “raw effluent from the sewer systems in Betio, Bairiki and Bikenibeu discharging into the intertidal reef flat area.” (MPWU, 2015). Faecal bacteria abundance harmful to human health has been consistently observed in the nearshore waters (Johannes et al., 1979; Naidu et al., 1991; Gangaiya, 1994; Abbott et al., 1995; NIWA, 2014a), which is not expected where sewerage infrastructure is adequate. Since the installation of the ocean outfalls in 1983–4 (Naidu et al., 1991), inputs of human waste to the lagoon side should have decreased. The impact of these improvements unfortunately appears to have been undermined by pollution from other sources, which likely include: groundwater contaminated by latrines and septic systems, the practice of traditional beach defecation, domestic waste water and animal waste (predominantly pigs), storm water run-off, and organic material from the lagoon foreshore landfills (Gangaiya, 1994; e.g. Hunt, 1996; Storey and Hunter, 2010; Mangubhai et al., 2019).

The sewage outfalls currently extend beyond the surf zone to a depth of 30 m at Betio, Bairiki, and Bikenibeu, and are fitted with 10 m diffusers (MISE and ADB, 2018). The use of salt water in the reticulated sewage system makes the outfall plumes less buoyant relative to the ocean water into which they discharge, and thus reduces the risk of their rising to the surface relative to a fresh water system. In our survey samples of surface waters in the vicinity of the Betio and Bairiki sewerage outfalls did not detect significant numbers of faecal bacteria, or evidence of eutrophication (see Fig. 8d). Elevated faecal bacteria abundance was observed at ocean shore sites near the causeways, where local direct inputs are not expected, which could indicate coastal transport of sewage inputs to the near shore waters. Sampling near the outfalls at a higher spatial resolution alongside hydrodynamic modelling

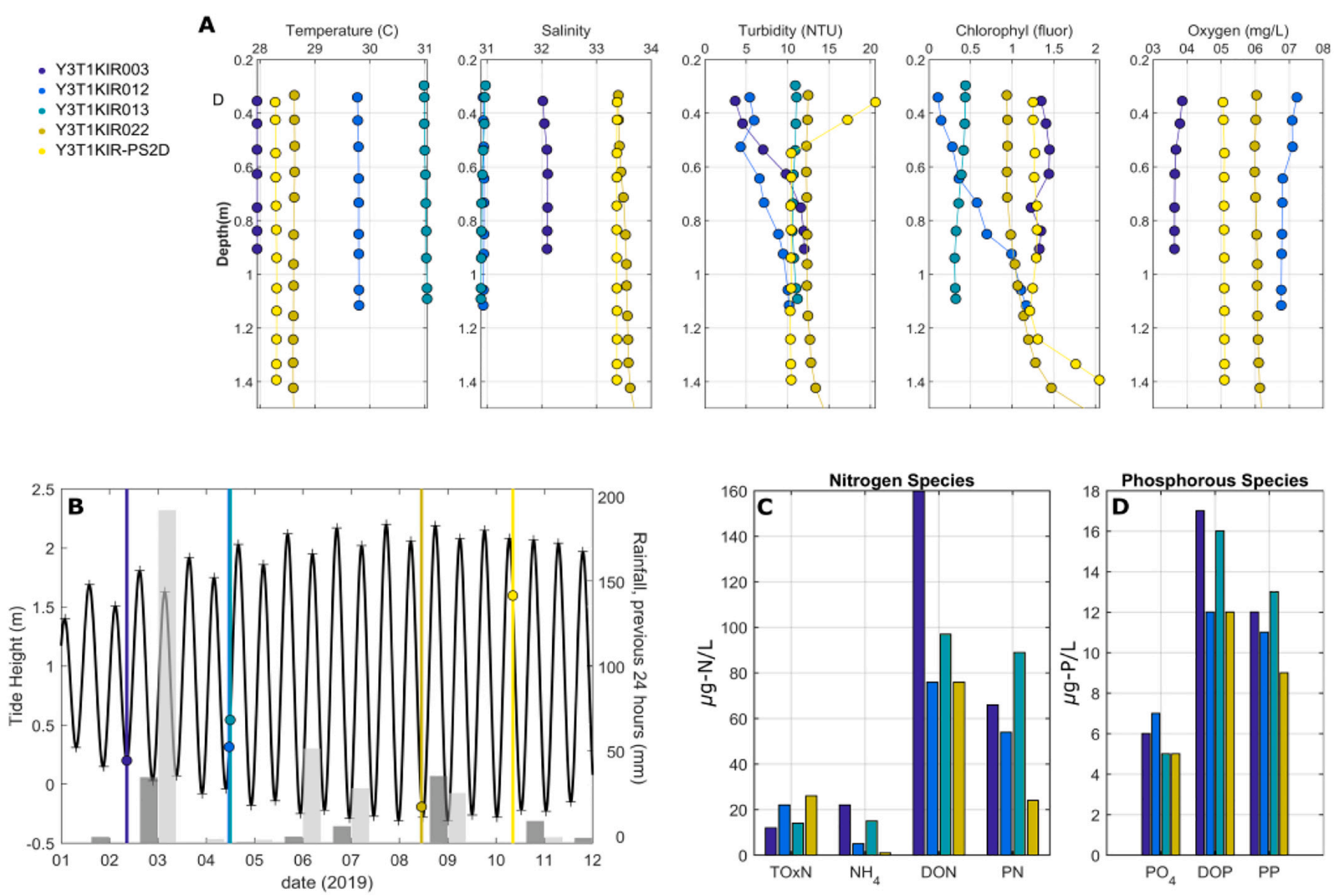

Fig. 6. Influence of tidal flushing at the milkfish pond outflow (sites 3, 12, 13 and PS2D) and inner lagoon (site 22). A: Depth profiles for upper 1.5 m of the water (full depth at pond outflows). B: Tides during survey (solid black line, left-hand axis) with sampling times shown by coloured circles and vertical lines and observed total daily rainfall from two South Tarawa Weather stations (grey bars, right-hand axis). C and D: surface water nutrient concentrations (not measured for PS2D). Daily rainfall information from synopic weather observations for Betio (Tarawa weather station, WMO station ID 91610) and Bonriki Airport (station ID 91612), obtained from the Kiribati Meterological Service (http://met.gov.ki/en/ob/synops, downloaded 16th May 2020). Tidal height from NOAA/NOS/CO-OPS Tide Predictions for Tarawa Atoll, extracted April 2019. Datum: MLLW (Mean Lower Low Water).

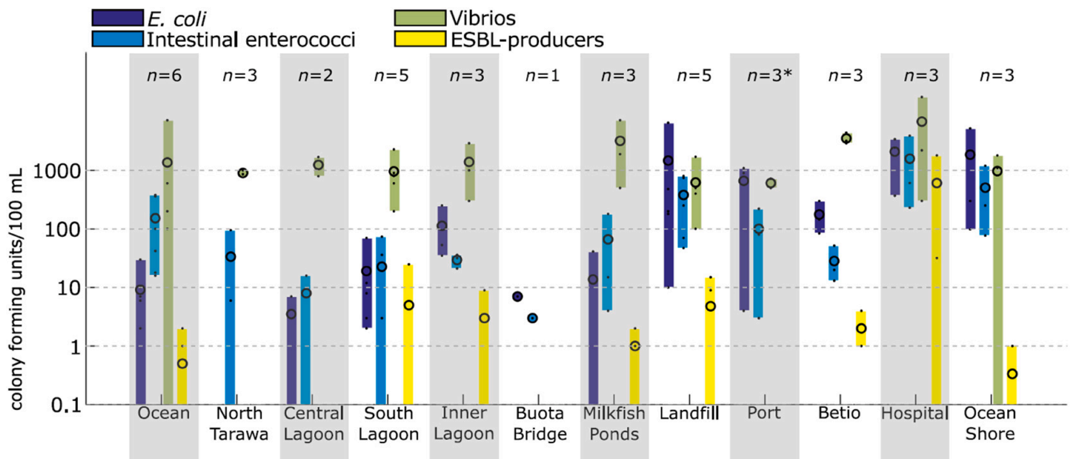

Fig. 7. Microbiological parameters summarised for site groupings (see Fig. 2 for site grouping locations). Coloured bars: range of values (minimum to maximum); large open circles: arithmetic mean; and small black points: individual observations. Samples for microbiological parameters were not collected at all sites, *n* gives the number of samples within each grouping. *for one Port site, vibrio and ESBL-producing bacteria were not determined. Minima extending to '0.1' on the y-axis indicate a 'not detected' site, and where no bar is shown for ESBL-producers they were absent in all samples within that grouping.

(e.g. Graham et al., 2020) or pollutant tracing is required to provide evidence of the present-day effectiveness of the sewage system in keeping waste away from the most intensively used near-shore areas.

The outfall at the hospital in Nawerewere, which is only a few kilometres east of the main Bikenibeu sewerage outfall, was not part of the 2017 improvement works (MPWU, 2015). Earlier water quality surveys reported historically high abundances of faecal bacteria near the old Bikenibeu hospital site, where hospital sewage was accumulated in a large holding tank and intermittently emptied and flushed on the outgoing low tide (Johannes et al., 1979). Now, at the Tungaru Central Hospital, an outfall pipe caries this waste off the reef edge, and an incinerator is used at the hospital to dispose of hazardous waste (MISE and ADB, 2018). Despite the improved sewage infrastructure, our samples collected from the concrete casing holding this discharge pipe where it was safely accessible from shore at both high and low tide stand out in our survey as a hot spot of faecal bacteria (Fig. 7; Fig. 8d). This is in contrast to the area being classified as 'safe for swimming' in the 2014 Kiribati Water Quality Report Card (NIWA, 2014a), which could reflect

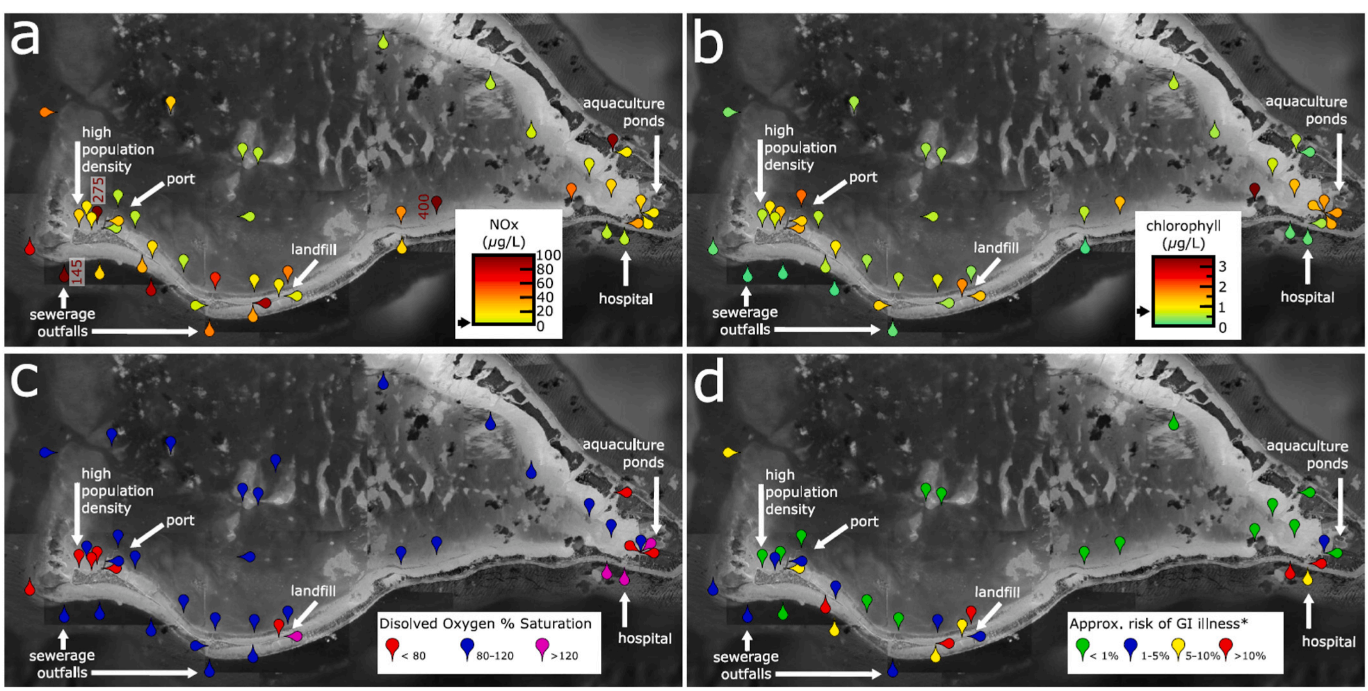

Fig. 8. Spatial visualisation of most severely impacted areas (labelled with white arrows). CME survey results compared to water quality assessment levels (thresholds) for selected water quality parameters: (a) nitrate+nitrite (NOx) concentration; (b) chlorophyll-a concentration; (c) surface water oxygen saturation; (d) single-sample intestinal enterococci abundance, compared to the single exposure risk of gastrointestinal (GI) illness *for 95th percentile values (WHO, 2003). For NOx and chlorophyll, relevant Default Guideline Values (DGVs) for tropical Australian slightly disturbed marine inshore ecosystems with clear waters (ANZECC and ARMCANZ, 2000) are indicated by black arrows on the colour-scales, and for dissolved oxygen concentrations red and purple symbols indicate values outside the relevant DGVs. White labelled arrows indicate locations of key pressures discussed in the text ('landfill' is Nanikai landfill located on the Anderson causeway, 'hospital' is Tungaru Central Hospital). In (a), NOx concentrations greater than the maximum colour scale are given numerically on the map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

increased discharge or emergence of cracks in the sewerage piping since 2014, or alternatively demonstrate the impact of high rain rainfall or other differences in sampling location or conditions. Our data show that these bacterial abundances were very variable in space and time even during our short survey period.

Short-term and small-scale variability in water quality is also evident around the Nanikai landfill. At high tide, lagoon water reaches the landfill wall and warm and fresh conditions (salinity 32.3 compared to nearby low-tide salinity of 33.4–33.5, and 3 °C warmer) suggest groundwater or surface freshwater flow into the lagoon. This low-salinity water carries a range of pollutants: high abundance of faecal bacteria as well as high concentrations of nutrients compared to other locations (Fig. 8a). These inputs drive high productivity evidenced by oxygen supersaturation (Fig. 8c) and elevated pigment concentrations (Fig. 8b). Other landfill-sourced pollutants, including metals, are also expected to be present in these waters (Carden, 2003; Redfern, 2006; NIWA, 2014b; Mangubhai et al., 2019). At low tide, the beach immediately adjacent to the landfill wall is exposed to about 150 m, so measurements of lagoon water from the same point are not possible. Beyond the intertidal zone a fresher water layer was present at low tide above a subsurface oxygen maximum which contained faecal bacteria abundance higher than adjacent sites, indicating that the tide was flushing these contaminated waters away from the shore. The highest bacterial abundances were not widespread due to dilution. The ability of tidal flushing to reduce nearshore faecal contamination, noted by Johannes et al. (1979), likely still plays an important role in removing pollutants from the most heavily used near-shore waters including landfills.

The milkfish (*Chanos chanos*) aquaculture ponds act as a source of nutrients into the inner lagoon, where water residence times are longest, posing the highest risk of poor water quality due to pollutant accumulation. Our sampling in this area demonstrates the extent to which the water quality observed at any time reflects a complex interplay between pollutant inputs, tidal mixing, and recent rainfall (see Fig. 6). The ponds and adjacent causeway were constructed in 1970 by 'reclamation' (conversion of marine area to terrestrial) of former lagoon flats of Temaiku (also spelt Temwaiku) Bight (or Gulf) (Biribo and Woodroffe, 2013). Aquaculture intensity has been variable (Naburennara, 1988; GOK, 2004). most recently operating as the 'Temaiku Ecofarm', reported to include 12 ponds stocked with 18,000 milkfish each in the early 2010s (Campbell and Hanich, 2014). The extent of aquaculture during the survey could not be confirmed, though the existence of the pond infrastructure and plans to increase Kiribati's aquaculture production (by 20%) in the context of National Adaptation (to climate change) is noted in recent plans (GOK, 2019). The open channels between North Tarawa islands connecting the lagoon to the ocean which are present near the inner lagoon waters have been shown to allow little water exchange during neap tide, and act as a source of ocean water into the lagoon during spring tides (Damlamian and Webb, 2008). These channels would therefore have allowed for some dilution of polluted waters accumulating in the inner lagoon related to the milkfish pond site, but without providing a route for pollutants to escape the lagoon. The residence time of water in this area of the lagoon was modelled as up to 70 days, compared to approximately 1 day before causeways linking all of the islands of South Tarawa were built (Damlamian and Webb, 2008).

The 'red beach' area near Betio (labelled 'high population density' in Fig. 8) has the shortest water residence times in the lagoon, being near the submerged western edge of the atoll and the deep shipping channel. These sites were selected because of the high population density of the area immediately adjacent to the lagoon shore; they had been identified as posing the highest risk to both human and coral reef health during the 2013–14 water quality monitoring programme (NIWA, 2014a, Mangubhai et al., 2019). While faecal bacteria were elevated off Betio compared to ocean and northern lagoon background, they remained an order of magnitude lower than other highly impacted sites, including the adjacent port. These differences in most at-risk areas between the two most recent Tarawa water quality surveys demonstrates the importance of sustained regular monitoring of impacted sites to understand the interactions between changes in pollutant inputs and changing dispersion, as is emphasized in the World Health Organisation's Guidelines for monitoring and characterising coastal bathing waters (WHO, 2003). The sewage infrastructure has been improved between the two surveys, which should have decreased direct inputs to this area if it led to an increase use of connected facilities. However, another difference is that the previous survey's samples were taken from shore, while the sites reported here were sampled from a small boat near high (falling) tide, 60–80 m from the edge of the beach, and our result could represent only a low-impact day or time of day.

Water column profiles show that the impacts of presumed inputs of organic material and nutrients extend off the reef edge into the ocean waters in this area (see Fig. 4). Near shore Betio sites were oxygen undersaturated (65–70%) indicating oxygen depletion due to aerobic breakdown of organic matter. This oxygen-depleted water was also observed in the top 2 m of nearby ocean water (Fig. 4). These waters may also be influenced by mixing with the highly oxygen depleted waters observed in the nearby port (60% saturation at low tide), which likely experiences direct waste inputs from boats and more restricted tidal flushing. Swimming and fishing were observed in the outer port during sampling, indicating that improved communication of the health risks from poor water quality is needed.

4.2. Physical factors controlling water quality

Water residence time in the lagoon was estimated as 10–15 days based on measurements of Kimmerer and Walsh (1981), whose detailed 1978 survey pre-dated the most significant alteration of the lagoon hydrology by causeways (Harper, 1988; see timeline in Fig. 1) and coastal engineering. A similar average lagoon residence time of 9.5 days was determined by computer modelling, with all current causeways in place, in 1995 (Chen et al., 1995). A more recent hydrographical model of the lagoon, at 100 m spatial resolution, estimated that during a spring tide more than 40% of the lagoon water volume is exchanged by tidal flushing each tidal cycle (Damlamian, 2008) with high spatial variability in lagoon water residence time. Damlamian (2008) compared lagoon circulation before and after closing of the southern Tarawa channels by causeways and found that the nearshore water along South Tarawa which previously had a residence time of 1–3 days is now expected to have a residence time of up to 70 days, significantly increasing the time during which pollutants can accumulate to harmful concentrations in these waters. This contrasts with the earlier modelling which suggested that opening of passages in causeways would increase water quality (for faecal bacteria) by only about 10% (Chen et al., 1995) Earlier studies have suggested that nutrient enrichment of coastal waters from human and animal waste discharge is not occurring to any significant degree in Kiribati (Kimmerer and Walsh, 1981; Gangaiya, 1994; Chen et al., 1995). This is no longer the case; observations of decreased water quality support the inference that the change in residence time has shifted the lagoon from being at low risk of becoming eutrophic to high risk.

The effects of tidal dilution on water quality, though widely acknowledged, have not been investigated as part of any water quality studies around Tarawa except for the early survey reported by Johannes et al. (1979) and Kimmerer and Walsh (1981) and the detailed multi-disciplinary work presented in Abbott et al. (1995). If tidal patterns were characterised, subsequent monitoring could account for this variability and ensure appropriate consistency in sampling to differentiate changes in water quality related to inputs from the effect of sampling at different tidal states. When the tide is low, the water on the lagoon side is not in contact with near-shore potential sources of human waste (for example, landfill walls). The water of the incoming tide would be expected to carry less shore-sourced pollutants. The risk from contact with nearshore waters is thus expected to vary throughout the daily tidal cycle, as well as between neap tides and king tides.

Rainy seasons are generally associated with reduced water quality, linked to increased river discharge and transfer of land-sourced pollutants to the coastal zone (e.g. WHO, 2003; Graham et al., 2020). Early investigations of gastroenteritis in Tarawa demonstrated a correlation between heavy rainfall and related hospitalisations (Kuberski et al., 1979). South Tarawa has no rivers, but heavy rains would be expected to lead to both surface run-off and groundwater flow into the coastal waters.

Kimmerer and Walsh (1981) documented dry conditions during their survey and a negative water balance in the lagoon (net evaporation). After the Dai Nippon (Betio-Bairiki) causeway was completed, Naidu et al. (1991) observed similar lagoon salinities, and therefore likely also sampled during a time of lower land-based pollution inputs due to drier conditions. NIWA (2014a) report an aggregated assessment based on samples throughout the year and thus integrate a range of different rainfall conditions. Our survey occurred during the typically wetter months (December–May) of the year (GOK, 2004), during an uncharacteristically wet year (Supplemental Fig. 1), which explains the dominance of freshwater inputs over evaporation in the lagoon making these waters less saline than oceanic.

Reporting water quality monitoring alongside salinity and rainfall observations, as well as including rainfall in hydrographical modelling could improve understanding of its impact on water quality. Kiribati experiences significant interannual variation in rainfall associated with El Niño Southern Oscillation (ENSO) patterns, characterised by wet and dry periods correlated to El Niño and La Niña episodes every 2–7 years where drought threatens the precarious freshwater availability in groundwater lenses (White et al., 1999; Werner et al., 2017). Naidu et al. (1991) report average total monthly rainfalls in Tarawa for the period 1946–78 of from 95 mm in October up to 325 mm in January, noting that the average total annual rainfall of 1945 mm poorly represents the variability with less than 1000 mm and greater than 3000 mm annual rainfall not being uncommon. Against a backdrop of such within-year and inter-annual natural variability, and limited historical information on rainfall, deconvoluting anthropogenic changes in pollution inputs from variable rainfall during and preceding sampling poses a challenge.

4.3. Risks from vibrio and antimicrobial resistance

Vibrio cholerae are responsible for cholera, a 1977 outbreak of which in South Tarawa (Kuberski et al., 1979) motivated the initial development of the sewage infrastructure (Naidu et al., 1991). Because of Tarawa's high risk of drinking water contamination with seawater during coastal flooding events (Werner et al., 2017), high abundances of vibrios in the nearshore marine environment around South Tarawa are a cause for concern, though not all vibrios cause disease (WHO, 2003). Locations where the highest abundances of vibrios were determined (Tungaru Central Hospital, Betio near main port, and milkfish pond outflow) are all extensively used by the local population, who were observed fishing and bathing in these waters during sampling. Pathogenic vibrio in Tarawa's coastal waters pose a human health risk in addition to the contamination from faecal bacteria which would not be specifically mitigated against by reducing inputs of faecal matter. During the 1977 outbreak, infection was connected to both contaminated drinking water and consumption of contaminated seafood (Kuberski et al., 1979). A recent study in Kiritimati, Kiribati's second most densely populated atoll, suggested that high abundance of vibrios (an order of magnitude less than observed at impacted Tarawa lagoon sites) was linked to a decrease in water quality and coral reef health (Dinsdale et al., 2008).

Vibrios occur naturally in the marine environment, with broadly variable abundances globally (e.g. Baker-Austin et al. (2013); EEEN (2013)). Vibrio abundance and outbreaks of vibrio-related disease, linked to rising ocean temperatures, are increasing (Baker-Austin et al., 2018). Improved understanding of environmental vibrio distribution at the global scale requires inclusion of observations from remote locations such as Kiribati.

The presence of antibiotic-resistant bacteria in the marine environment is gaining increasing attention in the context of the global health risk from increasing AMR (Taylor et al., 2011; Le Quesne et al., 2018). Pacific Island countries and territories, which have a hig burden of infections alongside limited healthcare resources, are at a particularly high risk (Loftus et al., 2020). To date, there is limited available information on the prevalence of human AMR-infections in Kiribati, with data likely reflecting testing heavily biased towards (or only in) patients in which first-line antimicrobial treatment has been unsuccessful (WHO: World Health Organization, 2014). In 2012 in Kiribati resistance to third generation cephalosporins was detected in 0% of *E coli* isolates (n=72), 1% of *Klebsiella pneumoniae* isolates (n=111) (WHO: World Health Organization, 2014); Foxlee et al., 2019; Loftus et al., 2020). To our knowledge, there are no previous measurements of AMR bacteria in the marine environment in the Pacific.

Hospitals are expected to be the primary source of antibiotics in South Tarawa, where their agricultural and aquacultural usage is not known to be widespread. Our survey confirms this assumption, with highest abundance of AMR bacteria observed in ocean waters adjacent to the Tungaru Central Hospital (up to 1790 cfu/100 mL), and potentially to a lesser degree also in lagoon waters near the Betio hospital. The two order of magnitude difference in ESBL-producing bacteria abundance observed between the high and low tide Tungaru Central Hospital site samples (Nawerewere) suggest that highest abundances may be dispersed and diluted at high tide but more detailed sampling over the tidal cycle is required to confirm this obvervation. Variability in inputs could confound clear tidal influence on abundance. In the vicinity of both hospitals, the elevated AMR bacteria risk appears to be limited to a distance of less than 1 km. Further investigation is required to understand to what degree AMR bacteria are reaching ocean waters from sewage, mixing back in towards the shore from outfall offshore, or from diffusive inputs into waters adjacent to the hospital. It is likely that the Tungaru Central Hospital's sewage infrastructure is in need of improvements, as it was excluded from recent sewage works (MPWU, 2015).

AMR bacteria were also detected in some, but not all, Nanikai landfill-wall samples, where metal contamination may also play a role (Baker-Austin, 2006; NIWA, 2014b). Potential risk is therefore not limited to the immediate vicinity of hospitals. A much more spatially and temporally comprehensive survey would be required to capture the variability of the risk and provide a better confidence description of these parameters to inform management. The presence of children playing and fishing activities in waters where extremely high numbers of ESBL-producing bacteria were found is of public health concern and supports further investigation into these relatively preliminary results.

4.4. Future monitoring, assessment, and mitigation

The environmental and human health risks of poor water quality in South Tarawa have been well recognised over the last 40 years. However, while infrastructure improvements and ongoing development of environmental policies (e.g. Tarawa Lagoon Management Plan, Abbott and Garcia, 1995a, 1995b) have worked towards reducing these risks (GOK, 2004), the snapshot of water quality status described herein demonstrates that significant work remains to be done to protect environmental and human health. Small-scale variability in space and time need to be characterised in order to deconvolute the various controls on water quality outcomes. It is important to co-measure human health and ecosystem health parameters (Wear, 2019), as well as physical and environmental parameters. The existing body of observational evidence, in terms of environmental monitoring, does not provide the necessary understanding of physical factors controlling water quality to allow informed decision-making with limited monitoring capacity and resources. The 1995 Tarawa Lagoon Management Plan stated that "without an ongoing system to monitor contamination levels, it will be

Table 4
Summary of observed water quality impacts. *An indication of risk is provided to indicate the level of concern given the status observed during March 2019 and in consideration of previous surveys and ongoing environmental pressures. Moderate: of concern for human health, ongoing monitoring recommended; High: leads to clear threats to ecosystem and human health; mitigation required; Very high: severe risk to human health, mitigation required.

Issue	Impact	Pressures	Snapshot from March 2019 survey	Risk*	Considerations for the future
Lagoon flushing and circulation	Ability of pollutants to be dispersed/diluted away from sensitive/high use areas	• Coastal modification, most significantly causeways restricting exchange between ocean and lagoon (e.g. Biribo and Woodroffe, 2013)	• Lagoon water less saline than ocean, indicating that freshwater inputs (rainfall/groundwater) dominate over evapotranspiration. • No evidence that sewage outfalls, which now extend off the reef-edge on the ocean side, are impacting nearshore waters.	High	• Discharge of planned desalination plant (OTEC) (Begg and Smith, 2016; Lee et al., 2016; Onorio, 2016) • Sewage inputs continuing to increase with population, sewage infrastructure aging (leaking outfall pipes) • Climate change impacts on seasonal and interannual rainfall patterns, tides, and sea level.
Eutrophication	Increased primary production, leading to dissolved oxygen depletion and restricted light availability, both threatening marine life	• Anthropogenic inputs as sewage and other waste (e.g. leaf litter (Gangaiya, 1994)) • Isolation of bottom waters from the atmosphere (reduced mixing, e.g. in inner port)	• Nutrient concentrations indicative of eutrophication throughout the survey area, with most elevated chlorophyll at impacted inner lagoon and near-shore South Tarawa sites compared to all ocean sites and lagoon sites further from expected human inputs. • Oxygen depletion in mid/bottom waters off Betio, and in port.	High	• Nutrient inputs likely to continue to increase. • Seagrasses habitats which offer many ecosystem services (Brodie, 2020; Brodie et al., 2020; Lincoln et al., 2021; McKenzie and Yoshida, 2020), are vulnerable to reduced water clarity. • Well-mixed shallow waters should continue to regularly have oxygen replenished from atmospheric mixing, while localised oxygen depletion is expected to increase in severity with increasing organic matter inputs • Deeper ocean waters near sewage outfalls, which do not appear to be well mixed vertically are additionally at risk of localised oxygen depletion.
Faecal contamination	Human infections through direct exposure to bacteria in the water or consumption of contaminated seafood	Human and animal (domestic pig) waste	• Widespread presence of faecal bacteria, with lowest abundances in North Tarawa and off-reef ocean waters. • Highly impacted sites around South Tarawa. • Abundance of *E. coli* and intestinal enterococci are patchy in space and time.	Very High	• Inputs will continue to increase with population, requiring further infrastructure investment to divert waste from highest-use areas. • Exposure to faecal material in coastal waters, or through related contamination of drinking water supplies during coastal flooding, could aid faecal-oral transmission of emerging pathogens, including SARS-CoV-2 (Xu et al., 2020)
Vibrios	Human infections through direct exposure to bacteria in the water or consumption of contaminated seafood	Increasing ocean water temperatures (at a global/ climate scale)	• Detected at all but 3 sites • Abundance at impacted sites both comparatively low (landfill and port) and comparatively high (milkfish ponds, Betio, and hospital).	Moderate	• Likely to be increasingly prevalent due to rising ocean temperature (Baker-Austin et al., 2018). • Increasing instances of tidal/ storm flooding contaminating fresh water sources is of concern and warrants future investigation in the context of changing climate.
Antimicrobial resistance	Human infections through direct exposure to bacteria in the water or consumption of contaminated seafood, which cannot be treated by many or all known antibiotics.	Increasing use of antibiotic treatment and escape of hospital waste into the marine environment.	No widespread risk , but extremely high abundances observed inconsistently in ocean waters near Tungaru Central Hospital.	Moderate	Increase is a global issue. Direct impacts could potentially be decreased by improving understanding of the localised hotspots observed near the Tungaru Central Hospital in Bikenibeu.

impossible to determine if progress is being made" (Abbott and Garcia, 1995a), which is still the case 25 years later. Intermittent monitoring in the lagoon, however, indicates that lagoon health has continued to deteriorate. The Kiribati Joint Implementation Plan for Climate Change and Disaster Risk Management recommends ongoing and improved water quality monitoring (GOK, 2019).

Key water quality issues and their impacts are summarised alongside an assessment of the current level of risk to Tarawa, as well as relevant future considerations in Table 4. Observations from the CME programme, in agreement with the previous survey of NIWA (2014a), indicate that water quality risks to environmental and human health in South Tarawa are high and, in the context of continued and increasing pressures, require mitigation. Continuing to improve the evidence base for the risks and consequences of Tarawa's poor water quality is crucial for increasing awareness of these issues. The challenge of prioritising water quality in Kiribati were well summarised by Jones and Lea (2007): "It has been difficult to get broader planning and urban management on the national agenda, as most of the population is preoccupied with the day-to-day survival needs of an over-populated atoll, as well as trying to supplement cash incomes with subsistence activities". The importance of effective communication and engagement with Tarawa's communities was highlighted by Dray et al. (2007), and there is an established need to recognise different 'ways of knowing' in the context of mitigating environmental issues (Kaiser et al., 2019).

Clear and informed communication of water quality risks to various stakeholders (communities, decision-makers and policy makers) is needed (e.g. Townhill et al., 2020). In terms of human health, the risk associated with exposure to contamination and appropriate communication depends on the uses and users of the water environment (WHO, 2003). The Kiribati Water Quality Report Card (NIWA, 2014a) is good example of a simple communication tool. However, it does not convey the complexity and variability of the system, nor was it followed up with sustained monitoring to determine, for example, to what degree subsequent sewage system improvements effectively mitigated the issues observed. Regular assessment of the water quality status, underpinned by a monitoring programme informed by an understanding of key processes and their variability, is needed.

5. Conclusions

The areas around Tarawa where risks of and from poor water quality are greatest are those in the vicinity of anthropogenic pollution sources: the main (Betio) port, a large landfill site (Nanikai), the inner lagoon (Temaiku aquaculture ponds), and adjacent to the Tungaru Central Hospital. The anthropogenic pressures on urban Tarawa's coastal environment are clear: high population density and waste inputs into the marine environment, combined with increased water residence time in the lagoon. Unfortunately, observations of the deteriorating water quality alongside change to pressures, which include modifications to aging sewage infrastructure and urban runoff associated with increasing population, have been too intermittent and incomplete to clearly demonstrate their impact. The current lack of monitoring contributes to the challenges faced in protecting coastal systems. Sustained ecological monitoring, alongside process-focused research studies, would allow Kiribati's decision-makers to advocate for continued investment in infrastructure, and help provide the information that could be used to positively influence behaviours of Tarawa's inhabitants. A robust observational evidence base would support prioritisation of management actions on water quality issues and thus help protect the resilience of Tarawa atoll to cumulative ecosystem and human health challenges.

Recent infrastructure projects have been accompanied by extensive Environmental Impact Assessments (EIA), in line with current regulatory requirements, reflecting increasing efforts to protect the marine environment and reduce health risks. However, there is still limited capacity both to carry out regular water quality monitoring and to enforce environmental stewardship in Kiribati. To allow robust connections to be made between changes in water quality, ecological functioning, and human health and changes in pollutant inputs future work should:

- make high-quality monitoring data openly and easily accessible for future assessments,
- co-record relevant physical parameters (tidal height, rainfall, precise location),
- include spatially focused surveys to build a solid foundation of understanding of small-scale variability, particularly in high risk areas.

Tarawa provides an extreme example of human pressures causing severe impacts on an atoll system where costal community and ecosystem health are closely interconnected. The comparison between the water quality conditions observed in Tarawa lagoon in 1978, when despite localised impacts the lagoon was found to be at low risk of eutrophication, and in 2019, with elevated nutrient concentrations, reduced dissolved oxygen and long lagoon water residence times, provides a warning for islands facing a similar trajectory of urbanisation coupled with limited water quality management resources. It highlights that maintaining good water quality requires not only mitigating the anthropogenic pollution inputs, but also consideration of how coastal modifications can reduce the system's ability to dilute and disperse polluted waters away from high-use areas and how cumulative pollution impacts evolve over time. Improved monitoring of coastal water quality where pressures from urbanisation are increasing, particularly in the context of cumulative impacts alongside the severe climate stress facing atoll communities, is needed to identify, understand, and manage both ecosystem and human health in these settings.

CRediT authorship contribution statement

Carolyn A. Graves: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Andy Powell:** Investigation, Methodology, Writing – review & editing. **Michelle Stone:** Investigation, Methodology, Writing – review & editing. **Farran Redfern:** Resources, Writing – review & editing. **Teema Biko:** Resources, Investigation, Writing – review & editing. **Michelle Devlin:** Conceptualization, Methodology, Supervision, Project administration, Funding acquisition.

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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Appendix A. Supplementary data

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