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Assessing the water quality of Suva foreshore for the establishment of estuary and marine recreational water guidelines in the Fiji Islands

Praneel Pranesh Lal[a], Natacha Juste-Poinapen M.S.[b] and Johann Poinapen[c,*]

[a] The University of the South Pacific, Suva, Fiji Islands
[b] Nucleus, Rotterdam, The Netherlands
[c] KWR Water Research Institute, Nieuwegein, The Netherlands
*Corresponding author. E-mail: johann.poinapen@kwrwater.nl

ABSTRACT

The Standards for water quality in Fiji defined in the Environment Management Regulations 2007 only relate to effluent discharge into the environment. Urbanisation is contributing to wastewater contamination in receiving estuary and marine recreational waters, thus requiring specific guidelines. To create a baseline for this, a sampling programme with relevant physico-chemical and biological parameters was implemented at 3 sites along the Suva foreshore, for 8 consecutive months, during low and high tides. Analysis was done in triplicates, using standard methods approved for the examination of water and wastewater. In the absence of relevant Fiji guidelines, the results were compared with ANZECC (2000) guidelines for estuary and marine waters. Low DO levels, high COD, TN, NH_3, TP, OP and heavy metal concentrations were measured in all 3 sites. For instance, TN and NH_3 concentrations as high as 4.44 $\pm$0.99 mg/L and 2.58 $\pm$ 0.89 mg/L respectively were recorded in Wailea river (Site 2). The colony counts for the *TC, FC and E. coli* were in most cases above the limits. These results confirm that wastewater discharges add to the inherent levels of parameters in receiving water bodies and support the need for specific, robust Fiji standards to better monitor water quality in foreshore areas.

Key words: baseline, biological parameters, indicator organisms, physico-chemical parameters, toxicity

HIGHLIGHTS

- Urbanisation contributes to wastewater contamination in Fiji water bodies.
- Development of water quality baseline is a pre-requisite for establishing water quality guidelines for water bodies.
- Use of indicator organisms to assess water quality affected by discharge of wastewater.
- Use of standard methods to develop baseline and water quality guidelines.
- Potential effect of tidal movement on water quality of estuaries.

INTRODUCTION

Wastewater discharge into receiving water bodies is a major environmental and public health concern in many countries resulting in global economic loss as high as $724,000,000 USD/year (Edokpayi *et al.* 2017; Onyango *et al.* 2018). According to the World Health Organisation (WHO), in 2019, 435 million people were taking water from unprotected wells and springs and 144 million people were collecting untreated surface water from lakes, ponds, rivers and streams. Moreover, Communicable Disease Surveillance Centre (CDSC) of the United Kingdom stated that contaminated fish, shellfish and their products are responsible for a significant portion of all food borne disease worldwide (Skinner *et al.* 2011) sometimes associated with high heavy metal and faecal coliform (FC) concentrations in molluscs (Government of Fiji 2007; Miedico *et al.* 2013). Many countries have set up agencies running monitoring programmes for surface water quality based on standards that include the safety limits for parameters which can pose a threat to aquatic ecosystems. Such parameters include nutrients, organics, inorganics and micropollutants (Schuwirth 2020). Also impacting water quality are variations in specific environmental indicators such as increase in biomass, heavy metal concentrations, loss of corals, limited biodiversity and nutrient pollution, toxins produced from harmful algal blooms and microplastics (Reichert *et al.* 2018). The limits defined in each standard vary from country to country as determined by their own reality. Among the globally recognised standards are the Australian and

New Zealand Guidelines for Fresh and Marine Water Quality (2000) supported by the Australian and New Zealand Environment and Conservation Council (ANZECC).

The lack of integrated assessment methods for the translation of individual measurements into overall assessment of water quality is still an issue in low- and middle-income countries, which revert to foreign standards as a reference to assess their own water quality (Bawiec *et al.* 2016). In the case of the Pacific Islands, the limitations of land mass, natural resources, wide spread territories and exposure to natural disasters results in serious water resource, solid waste and wastewater problems. However, limitation of data in coastal and fresh waters and the inability for the local government authorities to commit resources and establish necessary monitoring programmes was noted from a regional water quality survey done by Naidu *et al.* (1991) and is a cause for concern. If these Islands can establish their own water quality baseline data, they would consider the severity of their situation as well as consider the exposure patterns of identified pollutants, taking into account the variation in concentrations over time, according to pollution sources such as agriculture and sewer network. Also, they will account for the spatial variation exposure, which is dependent on position of point source within catchments, land use patterns and rate of discharge and dilution in river network (Schuwirth 2020).

As part of the Pacific Islands, Fiji has yet to complete their own, robust surface water quality baseline standards and mainly uses its national liquid waste standard from the Environmental Management (waste disposal and recycling) Regulations (Government of Fiji 2007), which characterise water quality meant for discharge only. It includes the following criteria; Temperature (°C), pH, Total dissolved solids (mg/L), Total suspended solids (mg/L), Total nitrogen (mg/L), Ammonia (mg/L), Total phosphorous (mg/L), Sulphate (mg/L), Cadmium (μg/L), Chromium (μg/L), Copper (μg/L), Lead (μg/L), Mercury (μg/L), Nickel (μg/L), Zinc (μg/L) and FC (mg/L). Previous studies (Mosley & Aalbersberg 2003; Maata & Singh 2008; Singh *et al.* 2009; Park *et al.* 2013) attempted to develop a limited water quality baseline but were characterised by sporadic measurements and a limited number of parameters analysed. For example, currently FC is the only microbial parameter to indicate contamination. However, this method is not considered accurate to assess faecal contamination since FC includes a range of bacteria and has recently been shown to detect thermotolerant bacteria in temperate areas (Odonkor & Ampofo 2013). In fact, updated ANZECC (2000) recommends *Enterococci* in marine and freshwater and *E. coli* in freshwater only, as indicator organisms for faecal contamination (Rodrigues & Cunha 2017). In other countries, testing for *E. coli* is done in conjunction with total coliform (TC) tests since TC indicates the potability of water as they are more resistant to treatment that kills *E. coli* (Maheux *et al.* 2014). Furthermore, several important and relevant water physico-chemical parameters should be added to the current Fiji standards, namely dissolved oxygen (DO), Chemical Oxygen Demand (COD), Nitrate, Nitrites and Ortho-phosphate since these parameters are key monitoring parameters in wastewater and treated sewage effluent thus high levels would indicate potential contamination (Bourgeois *et al.* 2001).

Accordingly, the purpose of this research is to develop a robust water quality baseline data of relevant physical, chemical and biological parameters, over an 8-month period, 4 months in summer and 4 months in winter, at both low and high tides for three main estuaries along the Suva foreshore, where an increase in recreational water activity has been noted, as a result of urbanisation. Such a baseline is currently not available in the Fiji Islands. This investigation used affordable advanced and approved standard methods. The ANZECC (2000) guidelines were used in this study as the main reference since they are most relevant to Fiji's tropical climatic conditions.

METHODS

Sampling programme

There are only two seasons in Fiji, the cool and dry winter is from May-October and the hot and wet summer is from November-April. Sampling was carried out from July to February, to include the warmest month (January), the coldest month (July) and the rainy months (December, January and February). The sampling sites (Figure 1) were chosen to represent the various critical receiving water bodies in the Suva estuaries and foreshore. Forests, plantations, formal and informal settlements and industrial zones are the major terrains the rivers and streams cover.

My Suva Park (Site 1) consists of a natural creek fed by seawater during the high tide and by runoffs during rainy seasons. The area is commonly used for recreational water activities such as swimming, boating and fishing. The water body in Wailea (Site 2), is mostly fed by the Vatuwaqa river, with industrial zones, service stations, communities and informal settlements that lack proper sewage networks, along its banks. During high tide, the water body is used for swimming, fishing and transportation. As for Centre Point (Site 3), the feeding Samabula river flows through forests, plantations, settlements and

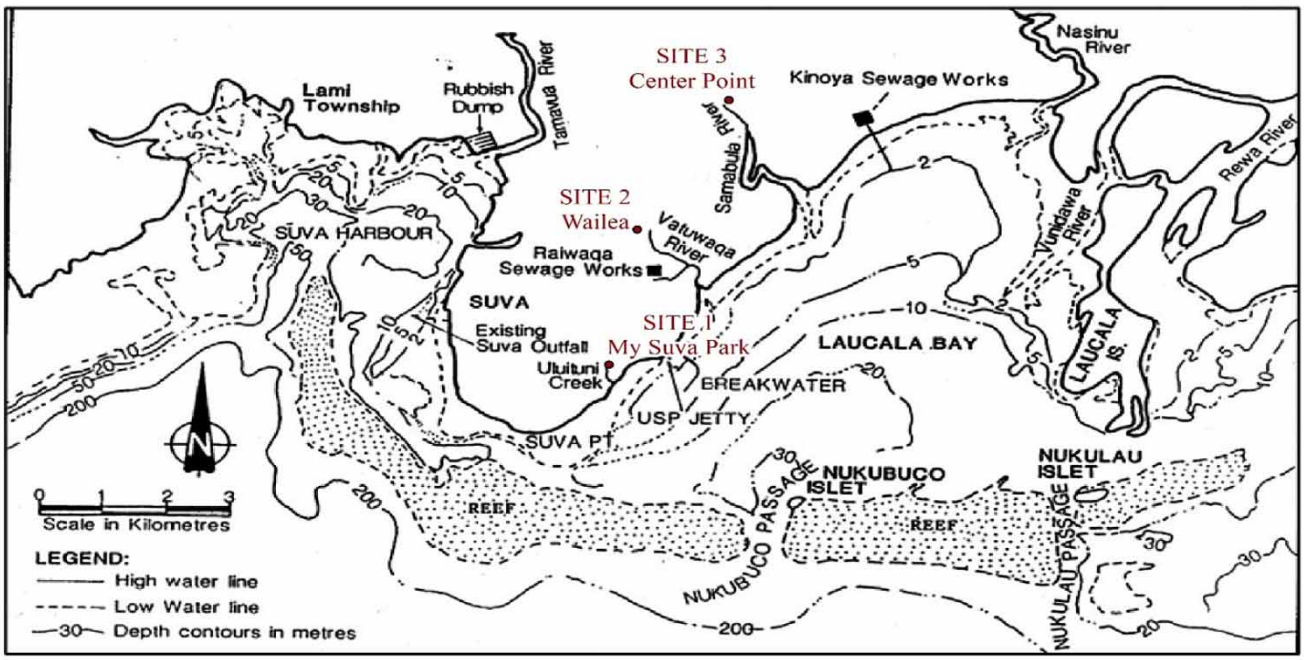

Figure 1 | Map of the study area showing the 3 sampling points (estuaries), namely My Suva Park (Site 1), Wailea Settlement (Site 2) and Centre Point (Site 3) that influence the Suva foreshore region as a result of urbanisation.

industrial zones. The Rewa dairy factory is located beside the river next to a sewage pumping station connected to the largest sewage treatment plant in Fiji, namely the Kinoya sewage treatment plant (Figure 1). The estuary acts as food source and recreation for people living nearby, as people practise snorkelling and net fishing.

Sample collection and storage

Water samples were collected from the 3 major sites, in triplicates, on the same day, at both low and high tides, based on the information from the Fiji Meteorological Service. Since most estuaries were approximately 1 m deep, a handmade sample collector, consisting of a pole with a sterile container at the end (Figure 2), was used to collect water, at approximately 30 cm, midstream, below the surface, before transfer into sterile polythene bottles (acid (HCl) clean) for chemical analysis and sterile glass bottles (autoclaved at 121 °C for 15 mins) for microbiological analysis.

All samples were placed in a portable cooler with ice, and brought to the analytical laboratory (Institute of Applied Sciences (IAS), The University of the South Pacific) within 2–3 hours from sample collection. Sampling was repeated at the end of each month, over an 8-month period from July 2017 to February 2018, to cover both summer and winter conditions. Each parameter analysis was done in triplicates for statistical analysis. For tests that could not be performed immediately, like heavy metals, COD, ammonia, nitrate, nitrite, total Kjeldahl nitrogen (TKN), orthophosphate, total phosphorous (TP) and sulphate, the samples were preserved and stored as follows: concentrated H_2SO_4 was added to 100 ml samples for COD, TP and ammonia tests and 500 ml volume for TKN analysis, to ensure the pH was maintained below 2. The samples were then stored at <6 °C for 7 days maximum. Filtered samples (100 ml) for Nitrate, nitrite and orthophosphate analysis were stored at <6 °C for maximum 48 hours. A 100 ml volume was also stored at cool 6 °C for maximum 28 days, for analysis of sulphate. As for heavy metals, concentrated HNO_3 was added 100 mL samples and stored at cool 6 °C for maximum 6 months. (Baird *et al.* 2012).

Calibration

Instrument calibration was carried out by the calibration unit of the accredited IAS laboratory. As part of the data quality assurance process, laboratory reagents and blanks were analysed and all analysis was done in triplicates. Standard reference solutions designated by the IAS laboratory were also systematically and routinely analysed to examine the accuracy of the methods.

Figure 2 | Handmade sampling stick consisting of a pole with a sterile container.

Selection of parameters

Physical and chemical parameters that are in the corresponding guidelines from ANZECC (2000) were considered as well as additional ones including conductivity, dissolved oxygen (DO), total nitrogen, total Kjeldahl nitrogen, nitrates, nitrites, total phosphorus and orthophosphate for these common organics upon accumulation from untreated effluent discharge, constitute organic pollutants. Total coliform and *E. coli* were supplementary to FC, as optional indicator organisms. All analysis were done at the IAS laboratory, using only approved Standard Methods for the Examination of Water and Wastewater (Baird *et al.* 2012) that have also been accredited for NZS ISO/IEC 17025 by the International Accreditation New Zealand (IANZ).

Physical parameters analysis

Physical parameters, namely temperature, pH, electrical conductivity, dissolved oxygen and total dissolved solids were analysed in-situ (on site), during sampling, using an Aquameter (AquaRead AquaProbe-2000D). The Aquameter was calibrated, according to the manufacturer's instructions before measurement. The data from the Aquameter was retrieved in Excel format using the Aqualink Aquameter software.

Total suspended solids

Sample collection for TSS was carried out mid-water depth to avoid interference with bed materials. A 100 ml of sample was well-mixed through, weighed (A) and put through a standard glass fibre filter of diameter 47 mm with pore size of 1.5 microns.

The retained residue on the filter was dried at 105 °C in an oven (Contherm Digital series) to a constant weight (B) as described in standard methods for the examination of water and wastewater (2540D). TSS was then calculated according to Equation (1) below.

$$\mathrm{TSS}\left(\frac{\mathrm{mg}}{\mathrm{L}}\right) = (\mathrm{A} - \mathrm{B}) \text{ /sample volume (L)} \tag{1}$$

where:

A = weight of filter + dried residue, mg,
B = weight of filter paper, mg

Chemical parameters analysis

Chemical oxygen demand

The COD was measured by digestion of 50 ml of sample with 5 g of mercury sulphate in the presence of 98% H_2SO_4 and potassium dichromate, followed by titration with ferrous ammonium sulphate, in the presence of ferroin indicator (Baird *et al.* 2012). The value was used in Equations (2) and (3) to calculate the COD.

$$Molarity\ FAS = \frac{Volume\ 0.04167M\ K_2C_{r_2}O_7\ solution\ titrated,\ mL}{Volume\ FAS\ used\ in\ titration,\ mL} \times 0.2500 \tag{2}$$

$$COD\ (mgCOD/L) = \frac{(A - B) \times M \times 8000 \times DF}{mL\ Sample} \tag{3}$$

where:

A = ml FAS used for blank,
B = ml of FAS used for sample,
M = molarity of FAS, and
8,000 = milliequivalent weight of oxygen × 1,000 ml/L

Total phosphate

The analysis of TP is carried out in two phases: digestion and colorimetry.

Digestion. First, 50 ml of the sample was digested for 30 mins at 120 °C in the presence of 1 ml concentrated sulphuric acid (98%) and 0.5 g potassium persulfate with one drop phenolphthalein indicator (2.5 g in 500 ml distilled water). The sample was cooled and 50 ml was transferred into the flask and one drop phenolphthalein indicator was added.

Colorimetry. Colorimetry was based on the Total Phosphorus Ascorbic Acid method. Then, 8 ml combined reagent (sulphuric acid, antimony potassium tartrate, ammonium molybdate and ascorbic acid) was added, and after 10 mins absorbance of each sample was read at 880 nm (Perkin Elmer UV/VIS Spectrometer, Lamda 35) and the TP was calculated as Equation (4) below. The calibration curve was prepared individually from a series of six standards as indicated in 4500-P.C.1c (Baird *et al.* 2012).

$$Total\ P(mg/L) = \frac{(Conc.\ of\ P(\mu g/L) \times Dilution\ Factor) - Blank}{1000} \tag{4}$$

where:

$Conc.\ of\ P\ \mu g/L$ = Concentration of P in the initial reading from UV.
DF = Dilution factor is the dilution ration of the sample.
$Blank$ = the sample blank used for curve calibration.

Orthophosphate

The orthophosphate ion (PO_4^{3-}) reacted with ammonium molybdate and antimony potassium tartrate under acidic conditions to form a complex that is reduced with ascorbic acid to form a blue complex that absorbs light at 880 nm (Perkin Elmer UV/VIS Spectrometer, Lamda 35) and the absorbance is proportional to the concentration of orthophosphate in samples (AP 4500-P, G). The linear calibration curve was established by plotting the absorbance of standards against orthophosphate concentration (Baird *et al.* 2012). Samples were analysed and the results were calculated using Equation (5).

$$P - PO_4\ (mg/L) = \frac{Conc.\ of\ PO_4(\mu g/L) \times DF}{1000} \tag{5}$$

where:

Conc. of PO_4 μg/*L* = concentration of PO_4 in the initial reading.
DF = dilution factor

Total kjeldahl nitrogen

Measurement of TKN was carried out in two steps, which are digestion of the sample in the presence of a high-selenium catalyst and strong acid (conc 98% H_2SO_4), followed by distillation in the presence of a strong base (50% NaOH) and reverse titration (AP 4500-N_{org}B). A volume of 50 ml of the sample, in the presence of 10 ml concentrated sulphuric acid, one catalyst tablet and 3 g analytical grade sodium sulphate was first digested in a digestion block (Gerhandt Kjeldatherm). Samples were then cooled to room temperature and distilled. The presence of nitrogen was indicated by the change in colour of the boric acid from purple to greenish. The samples were then reverse titrated using 0.01% hydrochloric acid. The molarity of HCl and TKN was calculated using Equations (6) and (7) respectively.

$$Molarity\ HCl = \frac{Mass\ of\ Borax \times 2 \times 1000}{Titre \times Mr\ Borax\ 381.37} \tag{6}$$

$$TKN(mg/L) = \frac{(Titre - Blank) \times MolarityHCL \times 14000 \times 50}{Sample\ Digested \times Aliquot} \tag{7}$$

where:

Mass of borax is the initial mass taken for the standardisation process.
Titre = the amount of acid used in titration.
Blank = the amount of acid used for titrating blank.
Sample digested = the volume of sample digested.
Aliquot = the volume taken for distillation.

Nitrate and nitrite

Nitrate is reduced quantitatively to nitrite by passing the sample through a copperised cadmium column. The resulting nitrite plus any nitrite originally in the sample was determined as a sum by diazotizing the nitrite with sulfanilamide followed by coupling with N-(1-naphthyl) ethylenediamine dihydrochloride. Water-soluble dye present after reaction had magenta colour and using absorbance of the colour was measured at 540 nm wavelength; absorbance of the colour gives results proportional to nitrate plus nitrite which is also known as total oxidised nitrogen. Recalibration and repetition of the sample analysis, without cadmium column can alone determine nitrite. Total oxidised nitrogen and nitrite flow injection method (Lachat Instruments Quick Chem 8500) were run in parallel to determine the concentration of nitrites, which was then subtracted from the corresponding concentrations of total oxidised nitrogen to give the nitrate concentration (Equation 8) in the samples (AP 4500-NO_3-I) (Baird *et al.* 2012).

$$N - NO_3\ (mg/L) = \frac{Conc.\ \ TON\ (\mu g/L) - Conc.\ \ NO_2\ (\mu g/L)}{1000} \tag{8}$$

where:

Conc. TON = concentration of total oxidised nitrogen in the samples.
Conc. NO_2 = concentration of nitrite in the samples

Ammonia

Samples containing ammonia or ammonium cation were injected into the FIA carrier stream (Lachat Instruments Quick Chem 8500) with a complex buffer (Disodium ethylenediamine tetraacetate (25.0 g) and sodium hydroxide (5.5 g) in 500 ml deionised water), alkaline phenol (Crystalline phenol 41.5 and 16 g sodium hydroxide in 500 ml deionised water) and hypochlorite (250 ml sodium hypochlorite 250 ml deionised water). Absorbance was measured at 630 nm wavelength with the peak area estimated as proportional to the concentration of ammonia in the sample as per Equation (9) below.

$$\mathrm{N-NH_3(mg/L)} = \frac{Conc.\ NH_3 \times DF \times 1.216}{1000} \tag{9}$$

where:

Conc. NH_3 = concentration of NH_3 in the samples.
DF = dilution factor

Sulphate

The sulphate ion, when exposed to an acetic medium in the presence of analytical grade barium chloride, forms barium sulphate ($BaSO_4$). Then, barium chloride suspension can be measured at a wavelength of 420 nm (Perkin Elmer UV/VIS Spectrometer, Lamda 35) and the concentration of sulphate ions was determined by the comparison of the reading with the standard curve (AP 4500-SO_4^{2-} E).

Heavy metals

The 4210 MP-AES with Agilent 4107 nitrogen generator was used to generate all the results. Using MP Expert software, background and spectral interferences were easily and accurately corrected. For each metal (Ni, Cu, Cd, Zn, Pb, Cr and Hg) analysed specific calibration curves were done by running freshly prepared standards from the stock solutions.

Biological parameter analysis

Once collected, the bottles containing samples were placed in a Coleman Esky cooler containing ice, and brought to the IAS laboratory within 2–3 hours for analysis to be performed within 24 hours of collection.

Sterilisation

Initial preparation of the microbiology sampling bottle included washing the bottle with Ezy clean dish washing detergent, followed by rinsing with tap water at least three times and with distilled water at least three times, to ensure the removal of chloride ions. Then upon drying, 1 ml of sodium thiosulphate (0.5 g/ml) was added into the bottle and autoclaved for 15 minutes at 121 °C (ALP Model MCY- 40 L).

Total coliform (TC)

To assess coliform bacteria, M-Endo agar and broths were prepared and analysis was carried out according to methods 9222B of APHA Standard methods for the examination water and wastewater, using microfiltration and plating (Baird *et al.* 2012). Incubation was at 35 ± 0.5 °C for 22–24 hours (Contherm digital). Colonies with pink to dark-red colour with metallic sheen on the surface, together with atypical colonies with dark red, mucoid and nucleated, without sheen, were counted using a colony counter (Suntex Colony Counter 570). The calculation of the number of coliforms (Equations (10) and (11)) and confirmation tests was carried out according to Baird *et al.* (2012).

LST Range 20–80

$$Number\ of\ coliform\ colonies\ cultured\ in\ LST = \sqrt{(20 \le x \le 80)} \tag{10}$$

where:

x = number of coliform colonies counted on the plate to be in the range from the lowest possible dilution.

$$TC = \frac{number\ of\ verified\ colonies}{total\ number\ of\ coliform\ colonies\ subjected\ to\ verification} \times Total\ count\ on\ plate \times DF \quad (11)$$

where:

Number of verified colonies = number of colonies positive after inoculation in the broth.
Total number of coliform colonies subjected to verification = number of colonies initially cultured into the LST from the plate.
Total count on plate = initial coliform colonies counted on the plate for verification.
DF = dilution factor for plate on which coliform colonies was counted between the range of 20–80.

Faecal coliform (FC)

For FC bacteria, methods 9222D of APHA Standard methods for the examination water and wastewater were used (Baird *et al.* 2012). Positive colonies from the total coliform test were transferred into 10 ml lauryl tryptose broth (LST) using 0.01-micron sterile loop and incubated for 48 hours at 35 ± 0.5 °C. Tubes showing gas formation and turbidity confirmed the presence of coliforms. Approximately 0.1 µl of the LST culture was used to inoculate each of brilliant green bile broth, incubated for 48 hours at 35 ± 0.5 °C, and EC broth, and incubated at 44.5 ± 0.2 °C for 24 hours. Gas formation with turbid brilliant green bile broth confirms the presence of total coliforms and gas formation with turbid EC broth indicated that the colony was FC. Equation (12) was then used to calculate the number of FC (cfu/100 ml).

$$FC = \frac{number\ of\ verified\ colonies}{total\ number\ of\ coliform\ colonies\ subjected\ to\ verification} \times Total\ count\ on\ plate \times DF \quad (12)$$

where:

Number of verified colonies = number of colonies positive after inoculation in the broth
Total number of coliform colonies subjected to verification = number of colonies initially cultured into the LST from the plate.
Total count on plate = initial coliform colonies counted on the plate for verification.
DF = dilution factor for plate on which coliform colonies was counted between the range of 20–80.

Escherichia coli (E. coli)

To assess *E. coli*, the standard method 9222G was used from standard method for the examination of water and wastewater (Baird *et al.* 2012). After the filtration process, the 0.45-micron filter paper was rolled on the freshly prepared m-FC agar to avoid entrapment of air. The inoculated plates were then incubated (Contherm digital series) at 44.5 ± 0.2 °C for 24 ± 2 hours. Various shades of blue colonies are produced by *E. coli* and non-FC (*Enterobacter, Klebsiella and Citrobacter*) produce grey to cream-coloured colonies. To further confirm the presence of *E. coli*, indole test was carried out on the blue shade's colonies. Positive results were indicated by a change in the amyl alcohol surface layer from yellow to dark red colour. Using Equation (13), the number of *E. coli* was then calculated.

$$E.\ coli(cfu/100mL) = number\ of\ various\ shades\ of\ blue\ colonies\ counted\ on\ plate \times DF \quad (13)$$

where:

Number of various blue colonies counted on plate = number of various blue coloured colonies counted and tested for positive results.
DF = dilution factor in which counts were possible.

Statistical analysis

Two tail t-test at α ($P \leq 0.05$) was used to test if the differences observed between samples were significant. Reproducibility was found at 95% confidence level. Standard error was also calculated to estimate the variance between populations at a confidence interval of 95%. Graphs were plotted in Microsoft Excel to illustrate the trends along time points and the limits defined by the Fiji Environmental Act discharge guidelines were included for comparison.

RESULTS AND DISCUSSION

The data analysed during the 8-month period for the three different sites were compared with relevant guidelines for estuary and marine waters from ANZECC (2000), as well as the National liquid waste standard in the Environment Management Regulations (Government of Fiji 2007), for water discharge in significant ecological zones. A t-test analysis on the mean values revealed no significant difference between high tide and low tide for the majority of the physical parameters, heavy metals, organics and nutrients measured. The mean value over the 8-month period and the standard error is presented in Tables 2–4 below.

Biological parameters analysis

At present in the Fiji Islands, no guidelines are available only for biological parameters for receiving water bodies commonly used for recreational activities. The ANZECC (2000) guidelines recommend the use of *E.coli* and *Enterococci* as indicator organisms for faecal contamination of fresh and marine recreational water. This study compiled results for three biological parameters, namely, TC, *E. coli* and FC instead of *Enterococci* was measured (Table S1 in Supplementary Information). The overall concentration of TC, FC and *E. coli* was much less in My Suva Park, in comparison to the other two sites, but fluctuated throughout the 8 months of the study (Figure 3(a)).

Research has shown *E. coli* as a better indicator for faecal contamination from human and/or animal sources (Odonkor & Ampofo 2013). The concentration of *E.coli* was compared with the limits of 130 cfu/100 ml (2.11 log cfu/100 ml) defined in ANZECC (2000). The results for My Suva park indicate a higher concentration of *E. coli*, compared to FC, in January (high tide: 2.63 $\pm$ 0.05 log cfu/100 ml; low tide: 2.65 $\pm$ 0.10 log cfu/100 ml) and February (low tide: 2.43 $\pm$ 0.14 log cfu/100 ml). In the case of the Wailea settlement and Centre Point, when considering the environment around the sampling sites (Figure 1), a high concentration of indicator microorganisms was expected and confirmed, as shown in Figure 3(b) and 3(c) respectively. The source of contamination could be the non-point discharge of sewage and wastewater into those receiving water bodies. Wailea is a known settlement with many people and the high concentration of *E. coli* could indicate that the sewage system needs upgrading to meet the needs of the growing population in that area. The main sewage pipeline to the Kinoya wastewater treatment plant runs across Centre Point (Figure 1) and the presence of *E. coli* in the water might suggest possible pipe leakages, justifying the use of additional biological criteria like *E. coli* as the indicator organism for faecal contamination and TC as an indicator for efficient water treatment.

Since no standards for FC was available in the ANZECC (2000) guidelines for estuary and marine water, the results were compared with the only available standard in Fiji, set up for water discharge (Environment Management Regulations, Government of Fiji 2007), where the acceptable limit for FC is 200 cfu/100 ml (i.e., 2.30 log cfu/100 ml). The FC concentrations in Site 1 was higher, except in February, August, September and October, for both high and low tides, and January during low tide only (Figure 3(a)). In cases where the FC concentration could be deemed acceptable, high values for TC were recorded. This is the case in January (high tide: 3.26 $\pm$ 0.05 log cfu/100 ml; low tide: 2.88 $\pm$ 0.13 log cfu/100 ml), February (high tide: 2.45 $\pm$ 0.08 log cfu/100 ml; low tide: 2.46 $\pm$ 0.14 log cfu/100 ml) and September (high tide: 3.22 $\pm$ 0.32 log cfu/100 ml; low tide: 3.56 $\pm$ 0.30 log cfu/100 ml) which indicates that the suitability of the water for recreational activities is questionable and might even suggest possible waste discharge (Karikari & Ampofo 2013; Maheux *et al.* 2014).

Figure 3(a) indicates an increase in TC concentration from low tide to high tide during the months of November, December and January. This period is characterised with high temperatures and intermittent heavy rains. An increase in recreational water activities, as well as runoffs from settlements with inadequate sewer systems feeding into the My Suva Park estuary during high tides, might have impacted the TC concentration.

The results show non-conformance with a known international standard for recreational water which can either mean poor water quality or reinforce the need for local guidelines defined as per existing conditions. Comparison with the guidelines for discharged water indicates that the biological characteristics of receiving water bodies are above the acceptable limit. Water discharge will contribute to further biological contamination which supports the need for more stringent limits and closer monitoring.

Physical parameters analysis

Since standard limits for receiving water bodies (estuary, marine and recreational) are yet to be established in Fiji, the average results recorded over an 8-month period (Table S2) were compared with relevant guidelines, namely the ANZECC guidelines for estuary and marine water quality (2000). Also considered were the standards for the discharge of National liquid waste in significant ecological zone (Table 1), as stated in the Environment Management Regulations (Government of Fiji 2007), to differentiate between the water characteristics. Temperature, pH, conductivity (EC), DO, TDS and TSS were categorised as physical parameters and are usually dependant on the environmental conditions, which differ from country to country. Therefore, while the temperature recorded at the three sites were in range to the international standards (Table 1), this is normal considering that the Fiji Islands are tropical.

The pH values for S1, S2 and S3 were 7.74 $\pm$ 0.13, 7.37 $\pm$ 0.06 and 7.36 $\pm$ 0.07 respectively and are within acceptable range if compared to the standard for liquid discharged in significant ecological zones (Table 1). Monitoring fluctuations of pH in natural waters is very important. For instance, hydrogen sulphide toxicity increases at low pH, due to the shift in chemical equilibrium towards an increase in its concentration (Boyd 2017). The pH also affects the solubility of the metal compounds combined in bottom sediments or suspended materials.

According to the results, high values for conductivity were recorded for all 3 sites, as shown in Table 2, in comparison to estuary and marine water quality limits. A similar observation was made for the TDS values recorded, in comparison with the ANZECC (2000) TDS guideline. According to ANZECC (2000), the TDS in an estuary should be between 3,000 and 35,000 mg/L, while in marine waters it is between 33,000 and 37,000 mg/L. Therefore, more data needs to be accumulated for the establishment of background limits for Suva estuaries and foreshore.

The TSS values for Sites 1, 2 and 3 were 26.2 $\pm$ 3.90 mg/L, 12.1 $\pm$ 2.83 mg/L and 10.7 $\pm$ 2.88 mg/L respectively and noted to be relatively high in comparison to ANZECC (2000) guidelines for marine water but below the estuary limit. This could be due to storm water introducing debris washed from the land into the system, decaying organic matter and causing tidal activities in the system (Schoellhamer 1996). A high TSS in the water column can lead to adverse impacts if the light penetration is reduced by 10% in an aquatic ecosystem, thus disturbing the food chain due to reduced photosynthesis. High suspended

Table 1 | Discharge standards of National liquid waste in significant ecological zones as listed in the Fiji Environment Management Regulations (Government of Fiji 2007)

A. Aesthetic Standard

Parameter		Indicator
Temperature		<38 °C
pH		7–9
B. Concentration Standard		
Parameter	Unit	Significant ecological zone
Suspended solids	mg/L	30
Total dissolved solids	mg/L	1,000
Coliform-faecal	c/100 mL	200
Sulphate	mg/L	300
Total nitrogen	mg/L	10
Ammonia	mg/L	5
Total Phosphorous	mg/L	2
Copper	mg/L	0.5
Cadmium	mg/L	0.05
Chromium	mg/L	0.1
Lead	mg/L	0.05
Mercury	mg/L	0.01
Nickel	mg/L	0.2
Zinc	mg/L	1

Table 2 | Comparison of the results recorded for the analysis of physical parameters at the 3 sites (My Suva Park, Wailea Settlement and Centre Point) along the Suva foreshore in the Fiji Islands with the guidelines for estuary and marine waters from ANZECC (2000)

	Measurements (mean ± standard error (@95% CI)			ANZECC (2000)	
Physical parameters	My Suva Park (Site 1)	Wailea Settlement (Site 2)	Centre Point (Site 3)	Estuary	Marine
Temperature (°C)	29.4 ± 1.06	28.4 ± 0.89	27.9 ± 0.57	29.6	–
pH	7.74 ± 0.13	7.37 ± 0.06	7.36 ± 0.07	5–9	6–9
EC (μS/cm@25 °C)	35,375 ± 5,355	15,391 ± 2,900	27,467 ± 6,670		–
Dissolved oxygen (mgO_2/L)	5.44 ± 0.57	2.68 ± 0.35	3.45 ± 0.20	>5	>5
Total dissolved solids (mg/L)	22,994 ± 3,481	10,004 ± 1,885	17,853 ± 4,335	3,000–35,000	33,000–37,000
Total suspended solids (mg/L)	26.2 ± 3.90	12.1 ± 2.83	10.7 ± 2.88	<75	<10

Table 3 | Comparison of the results recorded for the analysis of nutrients/organics at 3 sites (My Suva Park, Wailea Settlement and Centre Point) along the Suva foreshores in the Fiji Islands with the guidelines for estuary and marine waters from ANZECC (2000)

	Measurements (mean ± standard error (@95% CI)			ANZECC (2000)	
Nutrients/organics	My Suva Park (Site 1)	Wailea Settlement (Site 2)	Centre Point (Site 3)	Estuary	Marine
Total nitrogen (mg/L)	1.13 ± 0.17	4.44 ± 0.99	1.82 ± 0.41	0.3	0.12
Total Kjeldahl nitrogen (mg/L)	1.12 ± 0.16	3.96 ± 0.87	1.53 ± 0.33	–	––
Nitrites (mg/L)	0.0018 ± 0.0004	0.066 ± 0.009	0.032 ± 0.004	0.015[a]	0.005[a]
Nitrates (mg/L)	0.028 ± 0.007	0.423 ± 0.122	0.302 ± 0.074		
Ammonia (mg/L)	0.040 ± 0.014	2.58 ± 0.89	0.541 ± 0.281	0.015	0.015
Total phosphorous (mg/L)	0.33 ± 0.04	0.60 ± 0.11	0.51 ± 0.15	0.03	0.025
Orthophosphate (mg/L)	0.007 ± 0.004	0.328 ± 0.078	0.119 ± 0.033	0.005	0.01
Sulphate (mg/L)	1,430 ± 222	504 ± 104	988 ± 260	<400	–
Chemical oxygen demand (mg/L)	148 ± 21	64.1 ± 12.2	86.3 ± 17.8	<40	–

[a] NOx values used for ANZECC 2000.

Table 4 | Comparison of the results recorded for the analysis of heavy metals at 3 sites (My Suva Park, Wailea Settlement and Centre Point) along the Suva foreshores in the Fiji Islands with the guidelines for estuary and marine waters from ANZECC (2000)

	Measurements (mean ± standard error (@95% CI)			ANZECC (2000)	
Heavy metals	My Suva Park (Site 1)	Wailea Settlement (Site 2)	Centre Point (Site 3)	Estuary	Marine
Cadmium (μg/L)	0.710 ± 0.646	0.367 ± 0.230	0.140 ± 0.082	–	0.7
Chromium (μg/L)	9.57 ± 1.44	17.9 ± 11.3	11.8 ± 5.30	–	7.7
Copper (μg/L)	71.2 ± 14.7	23.8 ± 3.79	36.7 ± 10.9	–	0.3
Lead (μg/L)	0.88 ± 0.14	0.33 ± 0.05	0.56 ± 0.15	–	2.2
Mercury (μg/L)	0.026 ± 0.026	0.021 ± 0.021	0.069 ± 0.036	–	0.1
Nickel (μg/L)	1.35 ± 1.35	43.3 ± 34.5	18.8 ± 17.6	–	7
Zinc (μg/L)	47.6 ± 5.91	23.6 ± 3.14	42.7 ± 11.20	–	7

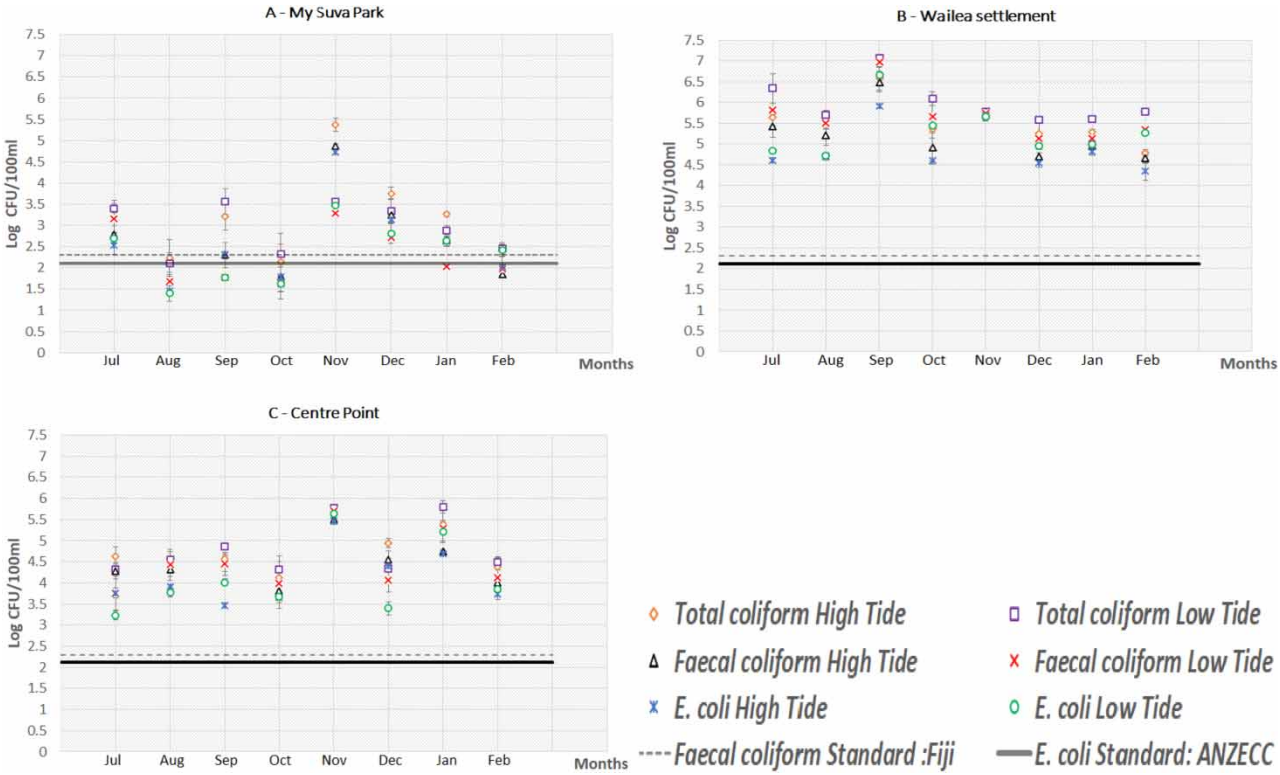

Figure 3 | Graphical representation of the mean concentration (log cfu/ml) of total coliforms (TC), (◊ High tide, □ Low tide), faecal coliforms (FC) (Δ × High tide, x Low tide) and *E. coli* (ж High tide, o Low tide) for My Suva park (A), Wailea settlement (B) and Centre Point (C). The standards for FC (dotted line) (Environment Management Regulations, Government of Fiji 2007) and *E. coli (*full line) (ANZECC 2000) WRE transformed into Log_{10} and included. Error bars represents the standard error with 95% confidence interval.

solids in the water can lead to poor visibility and can be dangerous for swimmers and divers. Marine organisms when exposed to high TSS concentrations face threats like death, reduction in the development of fish eggs (reduced gases exchange) and larvae, modification in behaviour and migration and reduction in food availability.

The three sites, namely My Suva Park (Site 1), Wailea Settlement (Site 2) and Centre Point (Site 3), recorded DO (mgO_2/L), values of 5.44 ± 0.57, 2.68 ± 1.35 and 3.45 ± 0.20, respectively (Table 2). The DO values are all lower than the ANZECC (2000) guidelines except for Site 1 which is slightly higher than the minimum ANZECC (2000) guideline for estuary and marine ecosystems. When assessing the DO values in the three sites, it is observed that tidal movement provides enough circulation to Site 1 water circuit system due to its close proximity to the foreshore, allowing efficient oxygen exchange, thus resulting in a relatively high dissolved oxygen concentration in comparison to the other two sites, while at Site 2 and Site 3, during high tide the water flow becomes stagnant, thus the organic pollutants move upstream causing a drop in DO values.

Analysis of organics and nutrients

Relevant organics and nutrients of interest were also analysed over the 8-month period (Table S3). The recorded COD (mgCOD/L) levels were 148 ± 21 (Site 1), 64.1 ± 12.2 (Site 2) and 86.3 ± 17.8 (Site 3) respectively. Although there is no set guideline for COD in marine water, a limit of <40 mg/L has been recommended for estuaries by ANZECC (2000). High COD concentrations suggest a greater amount of oxidisable organic material in the water body thereby increasing the oxygen demand (Edokpayi *et al.* 2017).

The TN concentrations measured at all three sites are notable when compared with the ANZECC (2000) guideline (Table 3), and it is a matter of concern as these values are recorded after dilution with the receiving coastal or estuary water. As for ammonia (mgN/L), elevated concentrations were noted for all three sites at 0.040 ± 0.014, 2.58 ± 0.89 and 0.541 ± 0.281 respectively and Site 2 reported concentrations much higher than the ANZECC (2000) guidelines. This could indicate illegal waste discharge or defective sewage systems at all three sites. Also, with the ANZECC (2000) guidelines stating the acceptable limit in both estuary and marine waters to be 0.015 mg/L, even the current limit of 5 mg/L for

discharged effluent (Government of Fiji 2007) needs to be revised as it also potentially contributes to an increased level of ammonia, leading to a toxicity increase in the receiving water bodies. Elevated concentrations of ammonia are acutely toxic to fishes, which is a concern since many communities along the foreshore rely on fishing for a living. Other potential organic pollutants included in the international standards were also measured. The level of nitrates was above the maximum acceptable limit for both the estuary and marine water quality guidelines.

Moreover, the concentrations of total phosphorus in comparison to ANZECC guidelines are significantly above the limits and similar findings were observed for the ortho-phosphate concentrations. High levels of phosphorous in the water could lead to toxic algal blooms, which could endanger many shellfish and fish with the toxins in addition to the stress of depleting oxygen availability (Ngatia *et al.* 2019). The major source of ortho-phosphate in the aquatic system at Wailea Settlement and Centre Point is from wastewater discharge into the rivers.

High levels of sulphate were also recorded for the 3 sites (Table 3), which is usually associated with wastewater discharge containing high concentration of fertilisers, fungicides, insecticides and sewage. This was the only parameter where tidal changes at Site 2 (Wailea settlement) impacted concentration significantly (Figure 4), ($P = 0.014$). This explains that there is a high effect of sea water at high tide in Wailea compared with the other two sites. Wailea water quality is mainly estuary during low tide and is significantly affected by sea water during high tide.

High organic loading leads to high oxygen consumption in the water bodies and the production of nutrient-rich water pockets leading to excessive algal growth (Ngatia *et al.* 2019). While limits defined in ANZECC (2000) guidelines can be used as reference for ammonia, nitrate, nitrite, total phosphorus, orthophosphate and sulphate, to include DO, COD and TKN in a list of parameters for monitoring the water quality in receiving water bodies along the Suva foreshore, this would require further analysis to set up the standard limits. For example, LC_{50} tests with different local species needs to be carried out in a controlled environment before defining the parameter concentration limits.

Heavy metals

High concentrations of heavy metals in the river water could be harmful to the species present in the water. To assess the toxicity concerns in the three water bodies, the concentration of heavy metals was analysed, namely for Cadmium (Cd), Chromium (Cr3+), Copper (Cu), Lead (Pb), Mercury (Hg), Nickel (Ni) and Zinc (Zn). The values recorded for Cr, Cu, Ni and Zn

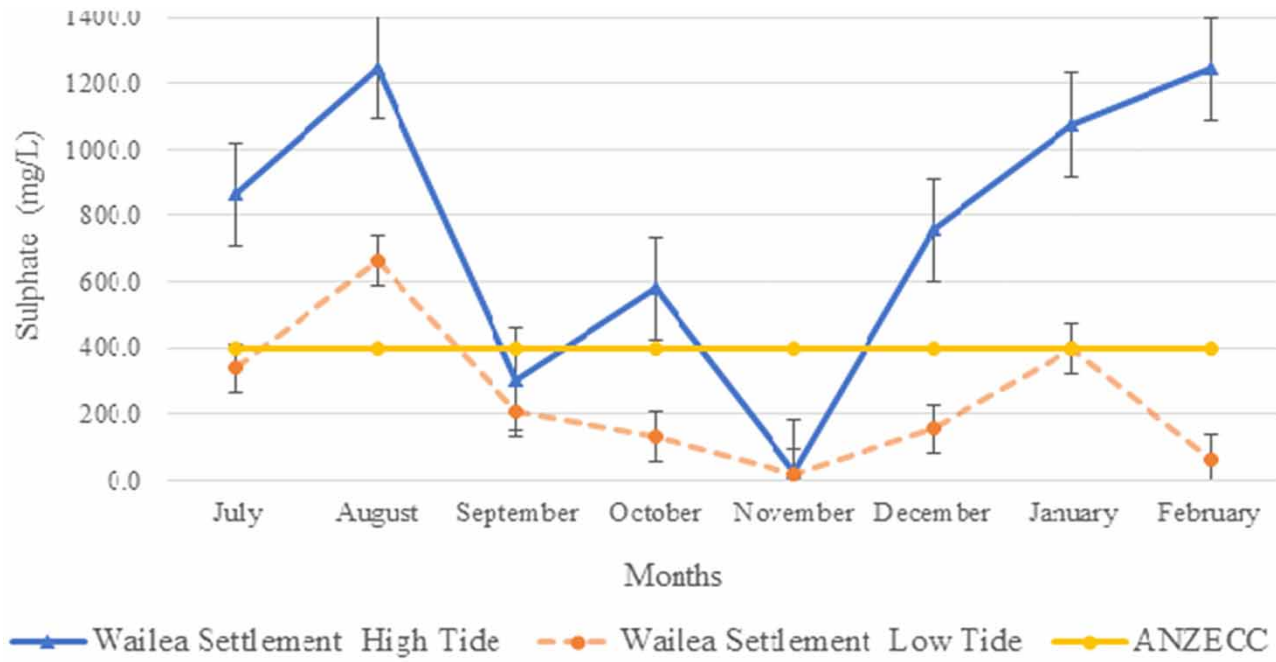

Figure 4 | Changes in sulphate concentrations (mg/L) during low tides (broken lines) and high tides for the period July 2017 to February 2018 at Site 2 (Wailea Settlement). The standard for sulphate limits defined in the ANZECC (2000) guidelines was included. Error bars represents the standard error with 95% confidence interval.

(Table 4) exceed the limits in comparison to the ANZECC guidelines, thus indicating potential toxicity concerns to the marine ecosystems.

Wailea river (Site 2) flows from industrial zones that include metallurgical, chemical and food processing industries, which probably could contribute to the elevated levels of heavy metals. However, Cr does not appear to accumulate at higher trophic level in the marine food web. To pass through a biological membrane, Cr should be in hexavalent form and once inside a biological system is generally reduced to Cr (III) (Oana 2006; Afshan *et al.* 2014).

In general, the concentrations of heavy metals in the water fluctuate at all three sites (Table S4). The levels reported for Pb, Hg and Cd for the three sites in comparison to ANZECC (2000) are within limits (Table 4). Lead concentration at Wailea Settlement (Site 2) and Centre Point (Site 3) could be the result of dumping of waste batteries and lead paints. My Suva Park (Site 1) is built on land that was previously barren, which ended up being a dump site where all sorts of rubbish was dumped, hence leaching of residual heavy metals could be from another source. Mercury tends to bioaccumulate in species and biomagnification takes place at high trophic levels. Mercury is most toxic in the form of methylmercury and nearly all fish and shellfish contains traces of methylmercury. Accordingly, this study provides a baseline for these heavy metal concentrations and how they change over time.

When considering these concentrations in the receiving waters, it is quite obvious that the discharge effluent concentrations need to be within the same magnitude to avoid any acute or chronic toxicity in the receiving water bodies. The heavy metal acceptable levels in the Fiji Environment Management Regulations 2007 are too high to avoid such toxicity and it is recommended to revise the limits with different LC_{50} test.

CONCLUSIONS

Overall, the study was able to establish a robust baseline dataset for T ^{o}C, pH, EC, TDS, TSS and the current concentrations of indicator microorganisms, organics, nitrogen, nitrates, ammonia, phosphorous and heavy metals along the Suva foreshore. The sampling period also accounted for spatial and seasonal variations and all analyses were done and validated using accredited methods and quality assurance and quality control (QA/QC). Although only three sites were chosen for this research, the outcome gives strong validity to assess more sites along the Suva-Nausori foreshore to establish a more expanded baseline that will represent the whole of this region. All results were compared with the ANZECC (2000) guidelines for estuary and marine water bodies. It was found that the concentrations of many water quality parameters were above the ANZECC (2000) limits and do raise concerns for potential environmental and public health impacts. If the receiving water environment is contaminated, people's livelihoods and health will be affected, leading to escalated health, social and economic problems. The extensive water quality data collected in this study can serve as a stepping stone to revise and expand the Fiji Environment Management Regulations (Government of Fiji 2007). This can be done by adding a new set of guidelines for recreational estuary and marine water bodies and encouraging additional studies to investigate the water quality of the rivers contributing to these estuaries as well as protected estuaries. In addition, the database thus created can serve as a baseline to monitor the changes in water quality with time and to assess if the water parameter concentrations are improving or not with time due to increased anthropogenic, agricultural and industrial activities. Furthermore, the database can serve as a reference for the Fijian authorities and stakeholders to assess the impacts of any intervention measures taken to improve the water and sanitation conditions of people living in these sites. The level of water infrastructure investment, namely installing new sewer lines and pumping stations depends on the resources available and the development plan of the Fiji Government and its partners. While waiting for this, people living along these river banks and foreshore could be trained and empowered to build robust septic tanks and improved existing ones to prevent leakage of sewage into the rivers and foreshore.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Afshan, S., Ali, S., Shaista Ameen, U., Farid, M., Bharwana, S., Hannan, F. & Ahmad, R. 2014 *Effect of Different Heavy Metal Pollution on Fish,* Vol. 2. Res. J. Chem. Env. Sci., 2 (1), 74–79

Agriculture and Resource Management Council of Australia and New Zealand. 2000 *Australian and New Zealand Environment and Conservation Council (ANZECC),* Vol. 1 & 2. Australian and New Zealand Environment and Conservation Council, Artarmon, New South Wales.

Baird, R. B., Clesceri, L. S., Eaton, A. D. & Rice, E. W. 2012 *Standard Methods for the Examination of Water and Wastewater,* Vol. 22, 22nd edn. American Public Health Association, American Water Works Association, Water Environment Federation, Washington, D.C.

Bawiec, A. J., Pawęska, K. & Jarząb, A. 2016 Changes in the microbial composition of municipal wastewater treated in biological processes. *Journal of Ecological Engineering* **17** (3), 41–46. doi:10.12911/22998993/63316.

Bourgeois, W., Burgess, J. E. & Stuetz, R. M. 2001 On-line monitoring of wastewater quality: a review. *Journal of Chemical Technology & Biotechnology* **76** (4), 337–348. https://doi.org/10.1002/jctb.393.

Boyd, C. E. 2017 Chapter 6 – General Relationship Between Water Quality and Aquaculture Performance in Ponds. In: *Fish Diseases* (Jeney, G. ed.). Academic Press, Auburn, AL, pp. 147–166.

Edokpayi, J. N., Odiyo, J. O. & Durowoju, O. S. 2017 Impact of wastewater on surface water quality in developing countries: a case study of South Africa. *Water Quality*. InTech, Vol. 1, pp. 401–416.

Government of Fiji, Ministry of the Environment 2007 *Environment Management (Waste disposal and recycling) Regulations 2007 (Vol 1).* Suva, Fiji.

Karikari, A. Y. & Ampofo, J. A. 2013 Chlorine treatment effectiveness and physico-chemical and bacteriological characteristics of treated water supplies in distribution networks of Accra-tema metropolis, Ghana. *Applied Water Science* **3** (2), 535–543. doi:10.1007/s13201-013-0101-6.

Maata, M. & Singh, S. 2008 Heavy metal pollution in Suva harbour sediments, Fiji. *Environmental Chemistry Letters* **6** (2), 113–118. doi:10.1007/s10311-007-0122-1.

Maheux, A. F., Boudreau, D. K., Bisson, M.-A., Dion-Dupont, V., Bouchard, S., Nkuranga, M. & Rodriguez, M. J. 2014 Molecular method for detection of total coliforms in drinking water samples. *Applied and Environmental Microbiology* **80** (14), 4074. doi:10.1128/AEM.00546-14.

Miedico, O., Pompa, C., Tarallo, M. & Chiaravalle, A. E. 2013 Assessment of heavy metals in bivalves molluscs of apulian region: a 3-years control activity of a EU laboratory. *E3S Web of Conferences* **1**, 11006.

Mosley, L. M. & Aalbersberg, W. G. L. 2003 Nutrient levels in sea and river water along the 'Coral coast' of Viti Levu, Fiji. *The South Pacific Journal of Natural and Applied Sciences* **21** (1), 35–40. http://dx.doi.org/10.1071/SP03007.

Naidu, S. D., Aalbersberg, W. G. L., Brodie, J. E., Fuavao, V., Maata, M., Morrison, R. J. & Whippy, P. 1991 *Water Quality Studies on Selected South Pacific Lagoons.* Oceans and Coastal Areas Programme Activity Centre, United Nations Environment Programme, Nairobi, Kenya.

Ngatia, L., Grace Iii, J. M., Moriasi, D. & Taylor, R. 2019 Nitrogen and Phosphorus Eutrophication in Marine Ecosystems. In: *Monitoring of Marine Pollution*. IntechOpen, London, UK.

Oana, P. 2006 Chromium impact on marine ecosystem. *Bull. Univ. Agric. Sci. Vet. Med. Cluj-Napoca* **63**, 379–384.

Odonkor, S. T. & Ampofo, J. K. 2013 *Escherichia coli* as an indicator of bacteriological quality of water: an overview. *Microbiology Research*. **4**(1). doi:10.4081/mr.2013.e2.

Onyango, A. E., Okoth, M. W., Kunyanga, C. N. & Aliwa, B. O. 2018 Microbiological quality and contamination level of water sources in Isiolo County in Kenya. *Journal of Environmental and Public Health* **2018**, 2139867. doi:10.1155/2018/2139867.

Park, E.-K., Wilson, D., Choi, H.-J., Wilson, C. T. & Ueno, S. 2013 Hazardous metal pollution in the republic of Fiji and the need to elicit human exposure. *Environmental Health and Toxicology* **28**, e2013017. doi:10.5620/eht.2013.28.e2013017.

Reichert, J., Schellenberg, J., Schubert, P. & Wilke, T. 2018 Responses of reef building corals to microplastic exposure. *Environmental Pollution* **237**, 955–960. https://doi.org/10.1016/j.envpol.2017.11.006.

Rodrigues, C. & Cunha, M. Â. 2017 Assessment of the microbiological quality of recreational waters: indicators and methods. *Euro-Mediterranean Journal for Environmental Integration* **2** (1), 25. doi:10.1007/s41207-017-0035-8.

Schoellhamer, D. H. 1996 Factors affecting suspended-solids concentrations in South San Francisco Bay, California. *Journal of Geophysical Research: Oceans* **101** (C5), 12087–12095. doi:10.1029/96JC00747.

Schuwirth, N. 2020 Towards an integrated surface water quality assessment: aggregation over multiple pollutants and time. *Water Research* **186**, 116330. https://doi.org/10.1016/j.watres.2020.116330.

Singh, S., Aalbersberg, W. G. L. & Morrison, R. J. 2009 Nutrient pollution in Laucala Bay, Fiji Islands. *Water, Air, and Soil Pollution* **204** (1), 363–372. doi:10.1007/s11270-009-0050-8.

Skinner, M. P., Brewer, T. D., Johnstone, R., Fleming, L. E. & Lewis, R. J. 2011 Ciguatera fish poisoning in the Pacific Islands (1998 to 2008). *PLoS Neglected Tropical Diseases* **5** (12), e1416–e1416. doi:10.1371/journal.pntd.0001416.

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