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ORIGINAL ARTICLE

Rainfall and land use impacts on water quality and communities in the Waimanu River Catchment in the South Pacific: the case of Viti Levu, Fiji

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Abstract

A community-based assessment along with a water quality framework was used to explore the Waimanu River water quality and to determine the impacts of the water quality on the communities which rely on the river for livelihood, sustenance, and recreation. Since both climatic and non-climatic factors affect the river system, the study used rainfall variability as well as land use assessments in addition to the community-based assessment to assess the effects of changing environmental factors on the river water quality. It was found that frequent rainfall intensified the runoff into the Waimanu River of contaminants arising from unsustainable land use practices in the Waimanu Catchment including agriculture, gravel extraction, logging, deforestation, and improper waste management. These led to physicochemical and microbial pollution in the river which augmented the vulnerability of the riverine communities to water pollution by hampering their food, water, income, and health securities. The river water quality is expected to further deteriorate as future climate change projections predict an intensification of annual rainfall events, thereby increasing river water contamination and risks to aquatic life and human life. Non-climatic factors that endanger water quality could be controlled by implementing better upstream land and waste management strategies on a catchment scale to minimize the adverse impacts of declining water quality on downstream communities. Methodologies employed in this study to monitor and maintain river water quality are applicable on a global scale to promote the health and security of riverine communities.

Keywords Rainfall · Land use · Flooding · River · Water quality

Introduction

Observation of variations in river water quality is essential since rivers are very important for the sustainability of ecosystems and human communities residing along their banks while being sensitive to the impacts of climate change and climate variability (Emanuel et al. 1985; Whitehead et al. 2006; ADB and WAF 2016; Begg et al. 2021). Rivers serve as a primary habitat source for freshwater organisms while humans have a direct dependence on freshwater for drinking, fishing, transportation, and recreational and industrial uses (Dudgeon et al. 2006). River water quality is usually modulated by natural and anthropogenic factors at both the river and catchment scales (Ahearn et al. 2005; Chang 2008; Chen and Lu 2014). Poor river water quality has severe impacts on the aquatic life and is not considered safe for recreational purposes (Nilsson and Renöfält 2008; de Andrade Costa et al. 2020; Santy et al. 2020).

Several studies quantitatively demonstrated a negative relationship between wet weather conditions and river water quality (Ferguson et al. 1996; Byamukama et al. 2000; Kistemann et al. 2002; Wu et al. 2012; Tornevi et al. 2014; Fan and Shibata 2015; Lebek et al. 2019; Abou Rafee et al. 2021). Nobre et al. (2020) observed that water quality impairment emerging from land use changes occurring adjacent to lakes in northeast Brazil was amplified by rainfall

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events. Shah et al. (2007) and Chen and Lu (2014) employed multivariate statistical methods to observe the impact of seasonal variations on river water quality parameters, concluding that temporal variations in water quality could be ascribed to frequent periods of intense rainfall. The need to maintain a high standard of water quality in the face of weather and climate variations poses a greater challenge for drinking water producers by increasing the costs of water treatment, which also involves laboratory water quality testing procedures in order to validate the adequacy of the treatment for the production of clean and safe drinking water (Delpla et al. 2009; Tornevi et al. 2014).

Freshwater contamination in the Pacific Islands

In Pacific Island Countries (PICs), pressures from economic development and unsustainable land use practices such as logging, deforestation, poor agricultural practices, improper sanitation facilities, and invasion of exotic species such as the water hyacinth (*Eichhornia crassipes*) coupled with climate change impacts lead to floods, landslides, soil erosion, sedimentation, and consequently, freshwater quality impairment (Mirti and Davies 2005; GEF et al. 2007; Boseto 2009; SPC et al. 2012; Connell 2015; Singh and Railoa 2020). Higher intensity of rainfall and flooding in PICs as a result of seasonal El Niño-Southern Oscillation (ENSO) events (BoM and CSIRO 2011) increases runoffs rich in nutrients and chemical fertilizers from agricultural land. Land management practices occurring upstream cause adverse downstream impacts on receiving waters and communities (Carpenter and Jones 2004; Begg et al. 2021).

Baisyet's research in 2002 revealed that in Fiji, 10% of the water demand is satisfied through direct rainfall and other sources. While Fiji's biodiversity is well-known for its richness and evolutionary adaptation, it is also an inextricable component of the traditional culture and identity of the local inhabitants (DoE 2020). Poor agricultural practices lead to the loss of riparian habitat and biodiversity, while creating soil erosion which increases the turbidity and sediment load of river water, reducing the availability of food for aquatic organisms (Tuttle-Raycraft and Ackerman 2019). The continuous loss of forests and destruction of watersheds in Fiji weaken the quality and availability of water supply for household and agricultural uses, and protection of riparian ecosystems is considered far more cost-effective than constructing and operating a water filtration plant (DoE 2020).

There is incidence of flooding caused by heavy rainfall and cyclone events during the Austral wet season (November to April), which is also the tropical cyclone season (BoM and CSIRO 2014; FMS 2020). In Fiji, the cool and relatively dry season is from May to October. Climate variability including natural climate patterns such as the ENSO which comprises of the El Niño (dry in Fiji) and La Niña (wet in Fiji), together with climate change are contributing to the variations in rainfall patterns which are projected to increase in the wet season and decrease in the dry season constituting a threat to river water quality in Fiji (Lata and Nunn 2012; BoM and CSIRO 2014; ADB and WAF 2016; GoF 2018; Chand et al. 2020). It is very likely that more frequent intense flood events caused by heavy rainfall will result in increased freshwater pollution (Douville et al. 2021). It has also been predicted with high confidence that higher water temperatures would intensify water pollution, aggravate water quality problems such as algal blooms, and reduce the concentration of dissolved oxygen (ADB 2013). This would exert more pressure on drinking water producers to provide clean and safe water to consumers (Mosley et al. 2004a, b).

Mosley et al. (2004a, b) evaluated the impact of tropical cyclone Ami on drinking water quality in Vanua Levu, Fiji, and discovered a significant deterioration of river water quality. The local water supplying utility faced difficulties in treating the contaminated river water to maintain a reliable supply of clean and safe drinking water to households. Moreover, Mosley and Aalbersberg (2003, 2005) analyzed the nutrient (nitrate and phosphate) concentrations at several riverine and coastal sites in Viti Levu, Fiji. They concluded that rivers had larger concentrations of nutrients attributed to the accumulation of human activities and large population in the study sites. In Fiji, a large proportion of the population relies on river water for subsistence, washing, bathing, and watering of livestock, livelihoods, transport of goods to markets, and recreational purposes.

Previous studies in Fiji have emphasized the hydrological elements of floods and intense rainfall events. However, there has not been any study in Fiji to elucidate the impacts of rainfall and human activities on river water quality, and the consequences on riverine communities. Our study employs both qualitative and quantitative assessments to explore the water quality in the Waimanu River in Fiji to support the formulation of efficient resource management strategies to control river water contamination at the catchment scale.

Study area

Geophysical characteristics of the Waimanu Catchment

The Waimanu Catchment is situated on the south-eastern windward side of Viti Levu, which is one of the two main islands in the Fiji archipelago (see Fig. 1). The windward side of Viti Levu Island is in the foothills of the central chain of mountains, topped by 1324 m high Mount Tomanivi, previously known as Mount Victoria (Soil Bureau, Department of Scientific and Industrial Research 1961). This topography

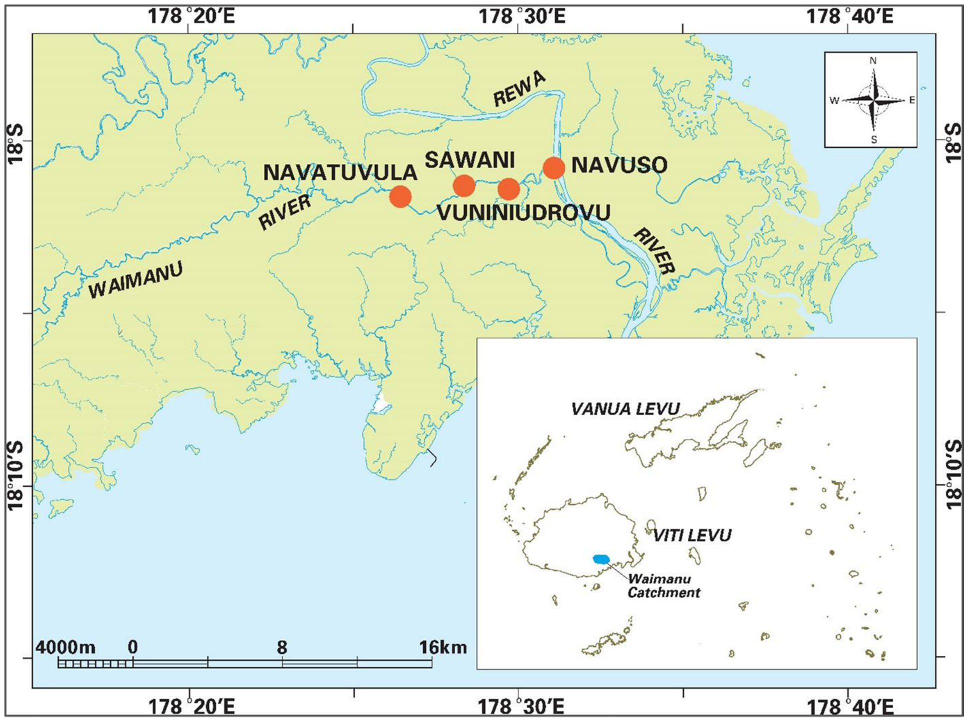

Fig. 1 Location of the Waimanu River Catchment in Viti Levu, Fiji (adapted from Begg et al. (2021))

creates a strong orographic effect, which maintains a regime of diurnal precipitation and modulates the amount of water entering the catchments below (Barros 2013). The Waimanu Catchment lies within the Nausori-Naitasiri topography and is a sub-catchment of the Rewa Watershed (Atherton et al. 2005), receiving one of the highest rainfalls in Fiji, ranging between 2500 and 4000 mm annually (JICA et al. 1998; Nausori Town Council 2012; ADB and WAF 2016). The Waimanu River (− 18°00′60.00″ South and 178°30′59.99″ East) has a total length of approximately 54 km (SPC et al. 2012). Figure 1 demonstrates the four riverine villages of the Waimanu Catchment examined in this study, having a total area of 165 km^2 (SPC et al. 2012). Navatuvula is the upstream community since there are no villages situated above it and Navuso is the downstream community located closest to the mouth of the river. Midstream communities (Sawani and Vuniniudrovu) are situated between the upper and downstream communities of the river (Begg et al. 2021).

Socio-ecological functions of the Waimanu River

The river water is pumped from the Waimanu and Waila intakes (shown in Fig. 2) to the Tamavua and Waila water treatment plants, respectively. After receiving treatment, the drinking water is supplied to the greater Suva area and to the eastern part of Viti Levu, which include a population of nearly 400,000 people (SPREP 2014). It is also a source of freshwater fishery on which the four riverine villages consisting of 192 households are dependent for subsistence and livelihood according to the Fiji Bureau of Statistics (2018). The freshwater clam (*Batissa violacea*), locally known as the “kai ni wai dranu” (ADB and WAF 2016) is a major source of protein in the diet of the local rural families (Lako et al. 2019). It also serves as the basis of substantial commercial fishery which is mostly operated by the indigenous (*iTaukei)* women in rural communities (Vunisea 2004; ADB and WAF 2016). The highest number of *kai* harvesters is found in the Naitasiri Province who harvest about 11,125 kg per week, amounting to around 78.6% of the total national value harvested (Lako et al. 2019). Freshwater fisheries are contingent on clean and oxygenated water for their survival (SPREP 2014; ADB and WAF 2016). Besides food harvesting, the Waimanu River is also used for recreational purposes such as boating, sport fishing, and swimming.

Data and methodology

Initially, secondary data was reviewed from journal articles and government reports to identify the impacts of climate change, climate variability, and human activities on the river water quality as well as to detect the consequences of the water quality on the communities in the Waimanu Catchment. In order to gather both qualitative and quantitative data, four methods were employed: (1) a participatory community-based assessment from Begg et al. (2021), (2) rainfall variability, (3) land use assessment, and (4) river water quality assessment. A participatory community-based

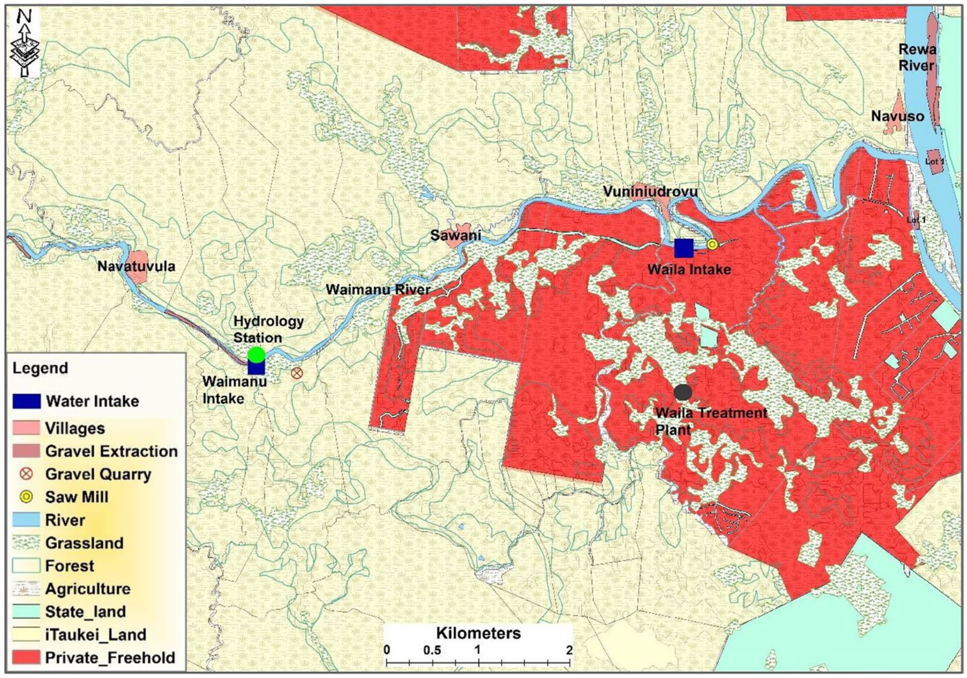

Fig. 2 Geospatial map of the Waimanu Catchment (modified after Begg et al. (2021)

assessment method provides opportunities for participants to reveal the social, economic, and environmental issues which they tend to face, and focus group discussions are the primary research tool used to conduct vulnerability assessments at local rural community levels (Van Aalst et al. 2008; Fazey et al. 2010).

The focus group discussions conducted as part of the community-based assessment in this study were based on a list of open ended as well as checklist type multiple choice close-ended questions to gather data on people's perceptions on the variability of rainfall and human activities in the catchment, the water quality of the Waimanu River, and the impacts of the water quality on the communities. The assessment process lasted approximately 5 weeks and encompassed eighty males and seventy-four females to enable mixed group discussions. A local research assistant familiar with the local *iTaukei* language and customary protocols was involved to help facilitate the discussions. Purposive sampling was used to select only knowledgeable people including community elders, leaders, and government and health workers as reliable sources of information when assessing the impacts of environmental changes on communities. The sampling procedure also ensured that respondents had been continuous residents of the selected communities for at least 30 years (Begg et al. 2021). The age category of participants ranged between 30 and 68 years (see Table 1).

Data collection and quality

Rainfall data

Focus group discussions (Table 1) were used at the community level to obtain qualitative data that is, people's opinions on rainfall trend in the Waimanu Catchment. Rainfall causes sudden alterations of the physical, chemical, and microbiological parameters of water by producing runoffs which further accelerate the transportation of contaminants from the land into the river systems (Kistemann et al. 2002; Wu et al. 2012; Tornevi et al. 2014). Therefore, daily rainfall data for the Waimanu Catchment was obtained from the Fiji Meteorological Service Headquarters for a 27-year time period (1994–2020) to perform the time series of the number of

Table 1 Number of focus groups and participants for each study site (adapted from Begg et al. (2021))

Village	Focus groups	Number of participants per group	Total number of participants	Total males	Total females	Age group
Navatuvula	6	5	30	13	17	35–60
Sawani	9	6	54	29	25	40–55
Vuniniudrovu	7	5	35	16	19	45–68
Navuso	7	5	35	22	13	30–65

days per year when rainfall exceeded 100 mm. This was the longest period of data available for this station. Rainfall data is generated at the hydrology gauging station located at the Waimanu Intake (Fig. 2).

River water data

Water quality parameters such as turbidity, temperature, dissolved oxygen (DO), total suspended solids (TSS), biochemical oxygen demand (BOD), orthophosphates (OP), and fecal coliforms (FC) are monitored by the National Water Quality Laboratory at the Water Authority of Fiji (WAF) which provided the data analyzed for this paper. The provision of quality drinking water to households is carried out by the WAF which is the sole drinking water utility in Fiji. Apart from provisioning drinking water across the country, the WAF also provides wastewater treatment services but the latter are limited to urban areas. The sampling analysis methods were identical during the duration of the data period (refer to Table A1 in Appendix A of the Supplementary Materials). Water samples to be tested for turbidity, TSS, OP, and FC were preserved in a cooler at a temperature of 4 °C and analyzed within 24 to 48 h after collection in sterilized glass bottles. Tests for temperature and DO were conducted onsite that is, at the intakes during sampling.

The water quality sampling results utilized in this study are for the river water samples collected from two points sourced from the Waimanu River (Fig. 2). River water pumped from the Waimanu water intake point is transferred to the Wailoku Depot (Tamavua Water Treatment Plant) which is situated outside the Waimanu Catchment Area, approximately 6.7 km from the Waimanu Intake. The Waimanu Intake pumps on average 36,000 m^3 on a daily basis and the Tamavua Treatment Plant has a capacity of 60 ml per day. The second point of collection that is, the Waila Intake, is situated downstream from the Waimanu Intake. This station draws on average 90,000 m^3 of water per day and pumps it to the Waila Treatment Plant located within the catchment, about 1.5 km from the Waila Intake (Fig. 2). The Waila Treatment Plant has a capacity of 100 ml per day.

When river water enters the intake chambers, it flows through metal screens which remove fish and debris such as sticks and leaves. The Waimanu and Waila intakes comprise of electrically operated submersible pumps which draw water from the Waimanu River and pump it to the corresponding Tamavua and Waila treatment plants. At the plants, pre-chlorination is done to destroy disease causing organisms and to control taste and odor causing substances. Subsequently, chemicals such as aluminum sulfate, sodium carbonate, and copper sulphate are mixed at the flash mixer. Sedimentation and coagulation processes are performed using clarifiers or sedimentation tanks. Next, rapid sand filtration is conducted using filter beds to filter out any remaining suspended particles. Finally, lime addition and post-chlorination dosing are done through an injector at the main line to complete the treatment process before pumping the treated water to the storage reservoirs for distribution to the customers.

Land use data

Analogous to the rainfall data, the same focus groups (Table 1) were used to obtain people's perceptions on the impacts of human activities on the water quality. Furthermore, biophysical data for the Waimanu Catchment was obtained from the Ministry of Lands and Mineral Resources to compile a geospatial map to depict the land use factors affecting the water quality of the Waimanu River.

Water quality assessment

A community-based participatory approach was utilized to gather perception data of communities on the water quality of the Waimanu River via the same focus groups mentioned earlier in the "Data and methodology" section. A conceptual framework was also utilized to quantitatively assess the water quality data of the Waimanu River and the results are demonstrated in the "Water quality at the upstream and downstream intakes" section.

Water quality framework

The water quality of a river describes the physical, chemical, and biological features of the water relative to its intended usage such as drinking, recreation, or for the sustainability of freshwater life (MoH 2005). Fiji does not have its own water quality assessment criteria for river water quality parameters. Therefore, it adheres to the water quality guidelines from the World Health Organization (Fewtrell and Bartram 2001), which are limited to the oxygen levels and microbial parameters such as FC to enable the assessment of aquatic life maintenance and recreational usages of the river water (MoH 2005; SPREP 2014). The European Union and the Organization for Economic Co-operation and Development (EU-OECD) (EU 1989; OECD 2008) and the United States Environmental Protection Agency (US EPA 1997, 2021) have also summarized the standards for several water quality parameters relating to the quality of river water intended for the abstraction of drinking, maintenance of aquatic life, and recreational usage.

River water extracted for drinking purposes is treated to eliminate or reduce the concentrations of contaminants and then tested according to the drinking water quality guidelines of the WHO prior to the distribution of the treated water to households for consumption. In contrast, untreated river water is directly used for recreation and its quality is also fundamental for the survival of aquatic life. When values for the water quality parameters including turbidity, temperature, TSS, BOD, OP, and FC exceed the standard criteria values for the specific usability, and values for DO are lower than the given criteria (refer to Table A2 in Appendix A of the Supplementary Materials), it is an indication of river water contamination. Subsequently, this impedes the usage of the river water for the intended purposes.

Scrutinizing impacts of river water quality

Perception data on the impacts of the water quality of the Waimanu River on the livelihoods and well-being of the communities was obtained using the same focus groups (Table 1). Qualitative data was also acquired from the National Water Quality Laboratory at the WAF to determine the impacts of the river water quality on the water treatment utility.

Statistical methods

Data for all water quality and rainfall variables were sorted for analyses and the measures for central tendency and variability were computed to provide a brief summary of the dataset (refer to Table A3 in Appendix A of the Supplementary Materials). Time series data helped to visualize the temporal trend of the variables which enhanced the comprehension of the long-term and short-term variations in water quality indicators attributed to changes in rainfall). Analysis of variance (ANOVA) was utilized to explain the impacts of seasonal changes in rainfall (wet versus dry) on water quality variations.

The primary measures of variability comprised of the minimum and maximum values (interval), and the coefficient of variation (CV). The study also employed the regression analyses to evaluate the long-term impact of a single predictor (rainfall) on seven response variables (water quality parameters) in the Waimanu River Catchment (Lavrakas 2008). Prior to conducting the regression analyses, all rainfall and water quality data were log-transformed using the natural logarithm to enable a near normal distribution and to reduce skewness. The statistical software for statistics and data science (STATA) was used to conduct the regression analyses.

The regression analyses were performed to obtain the estimated coefficients, *t*-statistics, standard errors, and probabilities for the predictor of the model. The output included seven equations, one for each outcome variable. The coefficients explained the amount and direction of variation in the predicted value of a water quality parameter relevant to a unitary change in rainfall. The coefficient of determination (*R*-squared) statistically measured the goodness of fit of the models in predicting the data points. The statistical analysis results are tabulated and presented in the following "Causality between rainfall and water quality" section.

Results and discussion

Impacts of rainfall on water quality

People's perceptions on rainfall

Participants from all four villages in the Waimanu Catchment area have observed rainfall becoming more frequent and intense over the years. A village elder who is a retired school teacher commented that "severe rainfall events have become more frequent over the past 50 years due to which the Waimanu Riverbanks easily overflow causing flooding in the catchment."

Causality between rainfall and water quality

Figure 3 shows the time series of the number of days per year between the period 1994 to 2020 when rainfall exceeded 100 mm. The intensity of rainfall in the catchment has increased over the past three decades predominantly in the wet season (refer to Table A4 in Appendix A of the Supplementary Materials).

This results in major discharges increasing runoff into the river (ADB and WAF 2016). The wet season which is also the cyclone season has a peak period between January and March (BoM and CSIRO 2014; FMS 2020). However, occasional formation of tropical cyclones outside the normal cyclone season that is, in the dry season months between May and October, is starting to appear as a result of climate change (FMS 2020). Some examples of off-season tropical cyclones in Fiji include category two tropical cyclone (TC) June which occurred in May 1997, category three TC Keli in June 1997, category two TC Lusi in October 1997, and category two TC Ella in May 2017 (Terry and Kostaschuk 2004; FMS 2017). This consequently increases dry season rainfall since tropical cyclones are accompanied with rainfall and floods. Nevertheless, the amounts of dry season rainfall are lower and less severe compared to the wet season rainfall. The time series analyses (see Fig. 4) reveal the 12-month periodicity in the plots of the variables over several years indicating that intense rainfall events and substantial levels of river water contamination have occurred in specific months that is, during the wettest months of a year.

According to the seasonal patterns in Fiji, November is the month recording the first severe rainfall every year upon the beginning of every wet season with progressive increases in the intensity of rainfall and in the levels of turbidity, temperature, FC, TSS, OP, and BOD, and reductions in the concentration of DO in the river water, in the subsequent months. As the relatively dry season approaches in May, the contamination level of the river water also starts to decline. Therefore, short-term variations in all the raw water quality

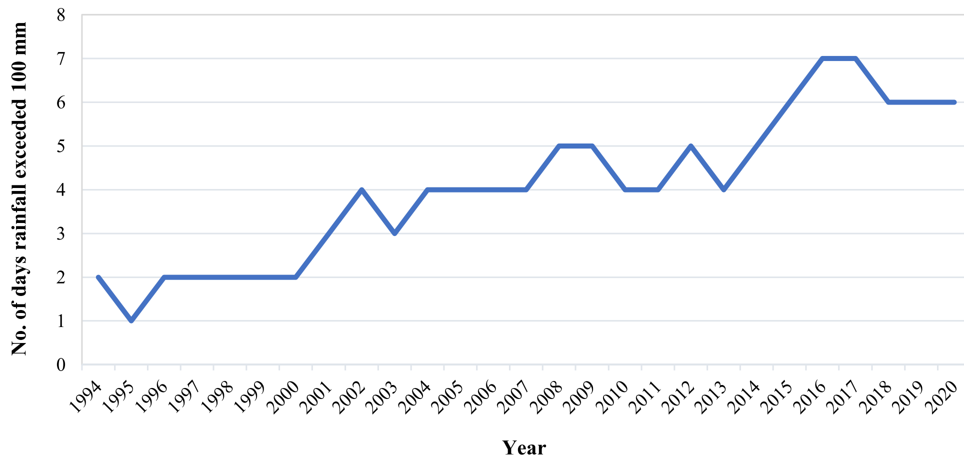

Fig. 3 Number of days per year with rainfall exceeding 100 mm in Waimanu Catchment

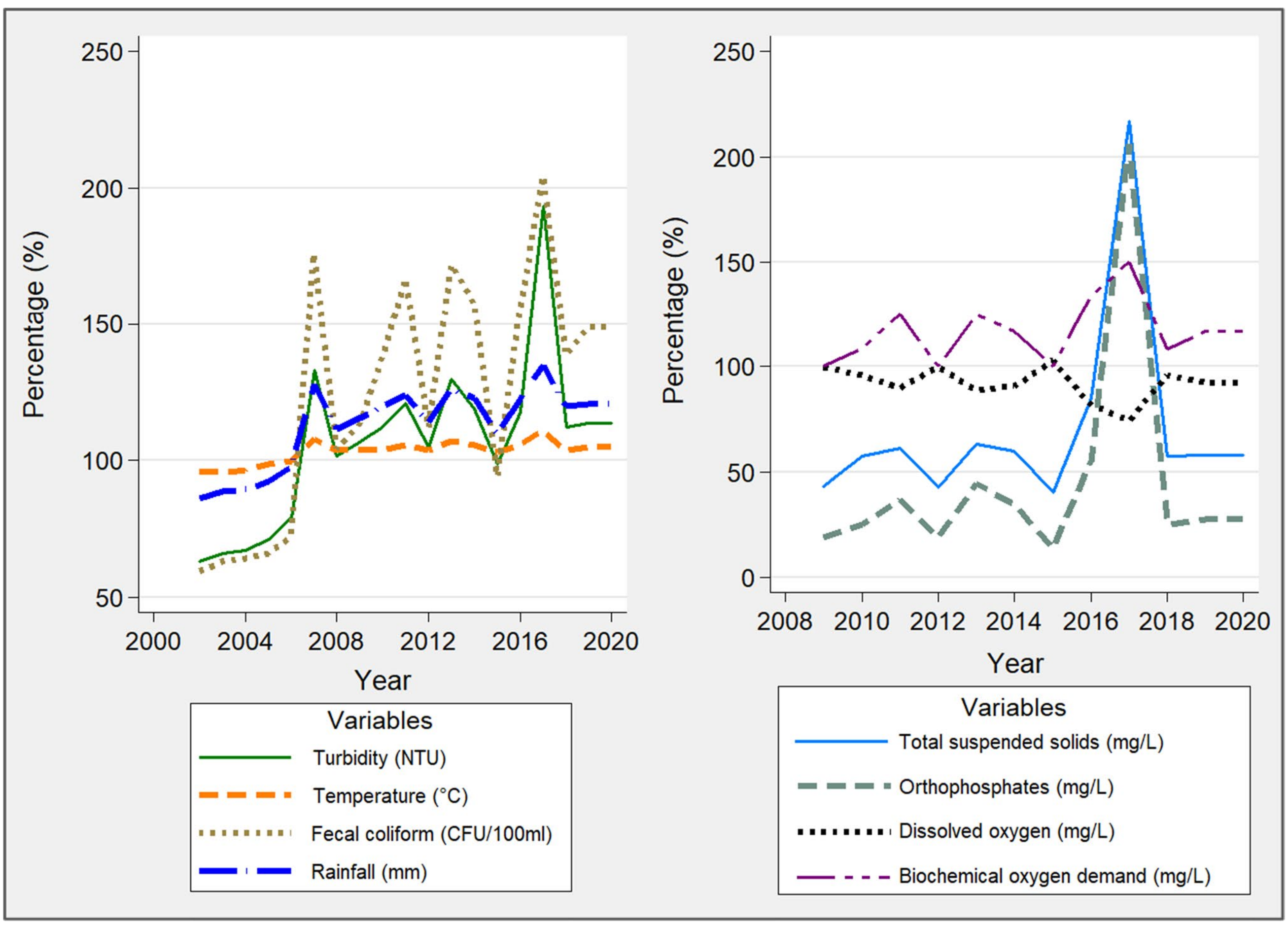

Fig. 4 Time series analyses of rainfall variable and water quality parameters in the Waimanu River Catchment (note: each variable has been linear transformed by expressing it as a percentage of its mean value) (data source: Fiji Meteorological Service (2020) and Water Authority of Fiji (2020))

parameters (between the period 2002 to 2020 for turbidity, temperature, and FC; and between 2009 and 2020 for TSS, OP, DO, and BOD) in the Waimanu River were ascribed to the seasonal changes in rainfall in the Waimanu Catchment. Moreover, the minimum level of DO in the river water and the anomalous peaks in rainfall, turbidity, temperature, FC, TSS, OP, and BOD in 2016 were associated with the occurrence of the TC Winston in February 2016 (FMS 2020). For time series data transformed by the natural logarithm, refer to Fig. B1 in Appendix B of the Supplementary Materials.

Analysis of variance was used to compare the variations in the water quality of the Waimanu River in each of the dry and rainy seasons. Tables 2 and 3 given below present the ANOVA of the seasonal changes in rainfall and variations in water quality parameters at the upstream and downstream water intake points, respectively. The extent of variability is highest among the observations of TSS and OP parameters (CV > 100%). All water quality parameters revealed significant seasonal variations ($p < 0.05$). Maximum values for turbidity, temperature, FC, TSS, OP, and BOD were reported in the wet season (November to April), whereas DO concentration levels were generally highest in the dry season (May to October). Minimal rainfall in the dry season indicated a less polluted river water quality.

Figures 5 and 6 illustrate the relations between rainfall and the water quality parameters at the Waimanu and Waila intakes, respectively. Turbidity, temperature, FC, TSS, OP, and BOD were positively correlated to rainfall while DO had an inverse correlation with rainfall.

Moreover, heavy rainfall accounts for most of the effect on water quality variables since a sharp increase in turbidity, temperature, TSS, BOD, OP, and FC and a sharp decrease in the levels of DO in the Waimanu River were observed above a rainfall of about 350 mm per month. The regression analyses for the upstream and downstream intakes shown in Tables 4 and 5 correspondingly demonstrate that the rainfall variable alone elucidates most of the variance in the overall water quality of the Waimanu River. Each of the seven univariate models was significant at the 5% probability level. Although the *R*-squared value for TSS was the lowest in comparison to the other water quality parameters at the upstream Waimanu Intake, the percentage of unexplained variance (22%) in the concentrations of TSS in the river water was still very small by climatological standards (refer to Fig. B2 in Appendix B of the Supplementary Materials). At the downstream Waila Intake, the *R*-squared value for OP (68%) was the least in comparison to the other water quality parameters. However, rainfall variable still had a pivotal role in influencing the concentration of OP in the downstream river water between the period 2010 to

Table 2 Analysis of variance of seasonal changes and variations in rainfall and water quality parameters at the upstream Waimanu Intake (data source: Fiji Meteorological Service (2020) and Water Authority of Fiji (2020))

Water quality parameters	Dry season		Wet season	
	Average {CV (%)}	Interval	Average {CV (%)}	Interval
Turbidity (NTU)	8.3{64}	0.25–32	16.6{60}	4.1–52.4
Temperature (°C)	24.1{8}	20–28.2	26.1{6}	23–29.5
DO (mg/L)	8.5{14}	5.44–11.4	6.6{21}	4.2–9.1
TSS (mg/L)	14.7{99}	0.4–105	59.9{108}	9.9–237.1
BOD (mg/L)	0.9{37}	0.1–1.9	1.5{28}	0.8–2.4
OP (mg/L)	0.3{217}	0.002–4.4	3.4{167}	0.07–25.5
FC (CFU/100 ml)	167{74}	21–566	331{50}	72–655
Meteorological variable				
Rainfall (mm)	228{31}	74–381	307{19}	171–433

(The assessment period was 19 years (2002–2020) for rainfall, turbidity, temperature, and fecal coliform (FC); and 12 years (2009–2020) for total suspended solids (TSS), orthophosphates (OP), dissolved oxygen (DO), and biochemical oxygen demand (BOD))

Table 3 Analysis of variance of seasonal changes and variations in rainfall and water quality parameters at the downstream Waila Intake between 2010 and 2020 (data source: Fiji Meteorological Service (2020) and Water Authority of Fiji (2020))

Water quality parameters	Dry season		Wet season	
	Average {CV (%)}	Interval	Average {CV (%)}	Interval
Turbidity (NTU)	38.5{61}	0.42–96.7	87.1{64}	24–334
Temperature (°C)	26.4{6}	22–28.8	28.1{4}	26–30.5
DO (mg/L)	7.5{17}	4.76–10.5	5.6{23}	3.2–8.4
TSS (mg/L)	86.9{66}	4.4–232	183.1{43}	49.4–491.4
BOD (mg/L)	0.9{37}	0.3–2.2	1.6{47}	0.6–3.51
OP (mg/L)	0.1{120}	0.002–0.93	2.1{237}	0.07–28.5
FC (CFU/100 ml)	312{37}	59–581	546{49}	250–1918
Meteorological variable				
Rainfall (mm)	253{24}	111–364	330{15}	227–429

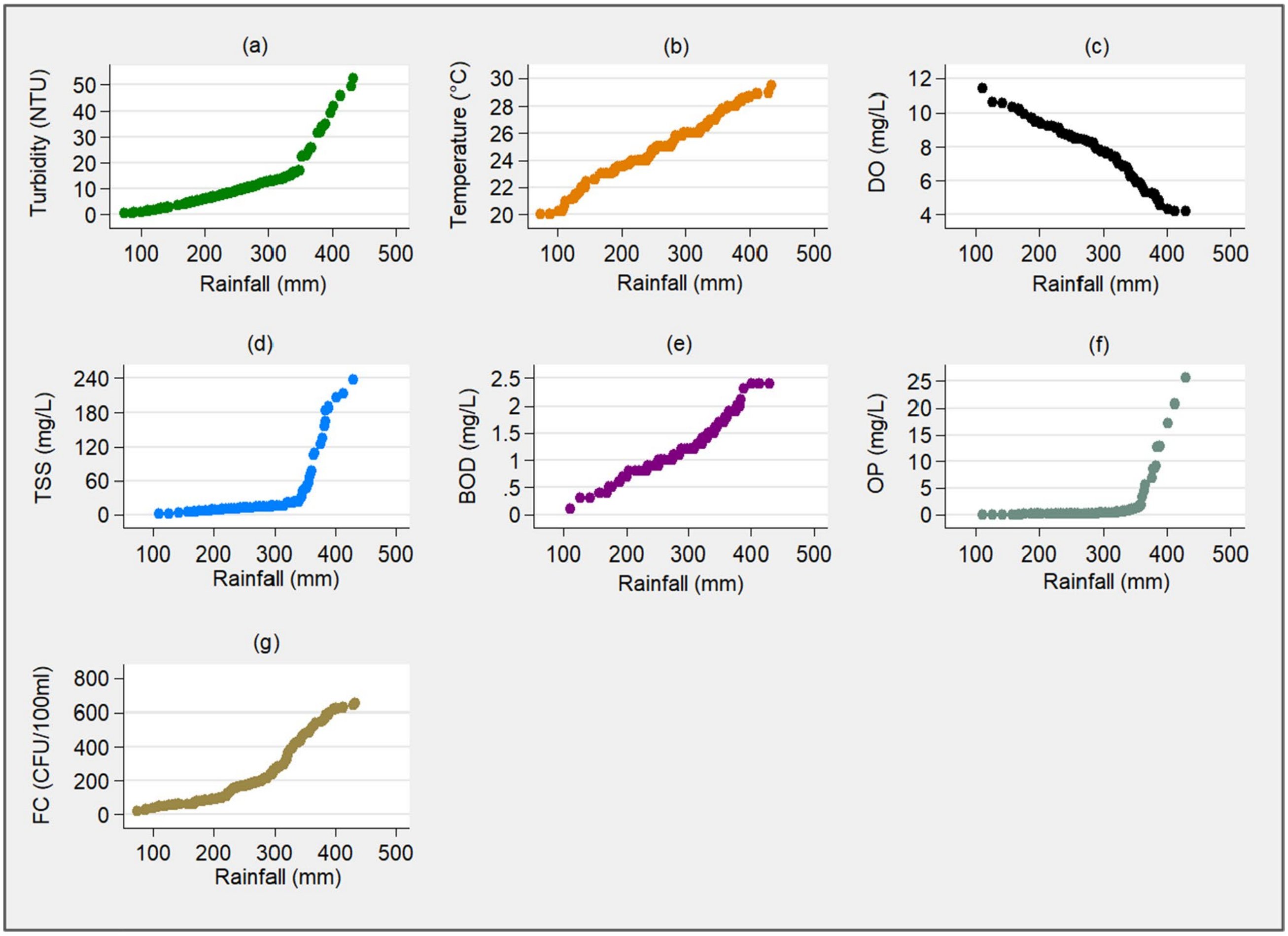

Fig. 5 Plots of relations between rainfall and water quality parameters measured at the upstream Waimanu Intake. From top left **a** turbidity (NTU), **b** temperature (°C), **c** dissolved oxygen (DO) (mg/L), **d** total suspended solids (TSS) (mg/L), **e** biochemical oxygen demand (BOD) (mg/L), **f** orthophosphates (OP) (mg/L), **g** fecal coliforms (FC) (CFU/100 ml) (data source: Fiji Meteorological Service (2020) and Water Authority of Fiji (2020))

2020. Furthermore, the variations in the river water quality could also be explicated by human activities such as the land use features of the Waimanu Catchment.

Impacts of human activities on river water quality

People's perceptions

One of the participants who is in her late thirties and employed in the private sector stated that "cattle, piggery and poultry farming on the riverbank areas deteriorate the river water quality by reducing the vegetation cover on the riverbanks." A middle-aged villager who is a nurse added that "wastewater released from open drains used by households flow into the river during heavy rainfall events resulting in poor water quality."

Land use practices in the Waimanu Catchment

Riverbank areas in midstream communities are mostly grassland unlike the presence of dense forest along the banks of the Waimanu and Rewa rivers in Navatuvula and Navuso villages. Arable farming is practiced throughout the catchment while pastoral farming is prevalent upstream of Sawani Village, both of which require frequent clearing of large areas of land and forests in order to cultivate root crops and to establish commercial livestock farms (Nath 2008; ADB and WAF 2016; Begg et al. 2021). Topsoil in areas with sparse vegetation is more prone to erosion while highly vegetated areas tend to absorb most of the runoff and prevent the contamination of water bodies (Nunn 2009).

Soil and riverbank erosion induced by unsustainable land use practices including shifting cultivation, logging activities, large-scale deforestation, and gravel extraction activities happening

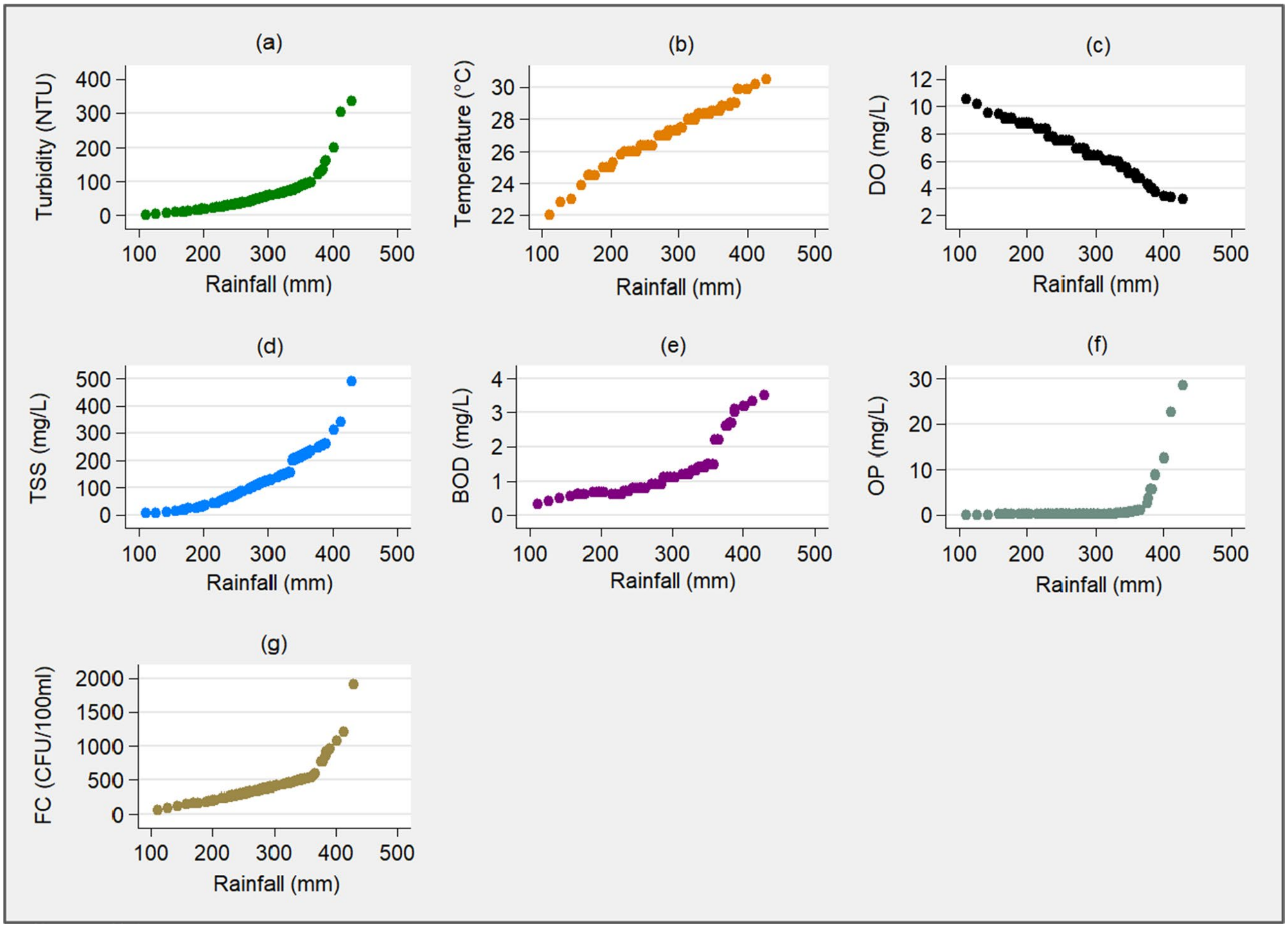

Fig. 6 Plots of relations between rainfall and water quality parameters measured at the downstream Waila Intake. From top left **a** turbidity (NTU), **b** temperature (°C), **c** dissolved oxygen (DO) (mg/L), **d** total suspended solids (TSS) (mg/L), **e** biochemical oxygen demand (BOD) (mg/L), (f) orthophosphates (OP) (mg/L), **g** fecal coliforms (FC) (CFU/100 ml) (data source: Fiji Meteorological Service (2020) and Water Authority of Fiji (2020))

Table 4 Regression analyses against upstream rainfall of water quality parameters measured at the upstream Waimanu Intake, using logarithms of monthly values for each variable (data source: Fiji Meteorological Service (2020) and Water Authority of Fiji (2020))

Water quality parameters	Number of observations	Regression equation	*R*-squared
Turbidity (NTU)	228	−4.730 + 2.373Rainfall	0.9680
Temperature (°C)	228	0.824 + 0.239Rainfall	0.9671
DO (mg/L)	144	2.799—0.787Rainfall	0.8088
TSS (mg/L)	144	−7.669 + 3.655Rainfall	0.7848
BOD (mg/L)	144	−4.402 + 1.819Rainfall	0.9598
OP (mg/L)	144	−17.417 + 6.891Rainfall	0.8740
FC (CFU/100 ml)	228	−3.100 + 2.237Rainfall	0.9468

(The data period for the analyses was 19 years (2002–2020) for rainfall, turbidity, temperature, and fecal coliform (FC); and 12 years (2009–2020) for total suspended solids (TSS), orthophosphates (OP), dissolved oxygen (DO), and biochemical oxygen demand (BOD))

above the Waimanu and Waila intakes are considered nonpoint sources of turbidity as they increase the rate at which suspended particulate matter enters the river system through sedimentation and siltation (Morrison and Clarke 1990; JICA et al. 1998; Begg et al. 2021). Suspended solids convey attached nutrients such as OP into the river water causing pollution (Uusitalo et al. 2000) (see relationship between TSS and OP in Fig. B3 in Appendix B of the Supplementary Materials).

Table 5 Regression analyses against downstream rainfall of water quality parameters measured at the downstream Waila Intake between 2010 and 2020, using logarithms of monthly values for each variable (data source: Fiji Meteorological Service (2020) and Water Authority of Fiji (2020))

Water quality parameters	Number of observations	Regression equation	*R*-squared
Turbidity (NTU)	132	− 6.501 + 3.332Rainfall	0.9550
Temperature (°C)	132	0.881 + 0.226Rainfall	0.9870
DO (mg/L)	132	3.038—0.911Rainfall	0.8426
TSS (mg/L)	132	− 6.097 + 3.307Rainfall	0.9935
BOD (mg/L)	132	− 4.265 + 1.754Rainfall	0.8285
OP (mg/L)	132	− 12.674 + 4.884Rainfall	0.6772
FC (CFU/100 ml)	132	− 2.068 + 1.895Rainfall	0.9326

Higher concentrations of OP are mostly influenced by runoffs from improper disposal of untreated human sewage and agricultural farms including animal waste, fertilizers, herbicides, weedicides, and pesticides (SPREP 2014). Natural processes such as weathering of volcanic parent material within the catchment also contribute to the increased concentrations of OP in the river water (Raj 2004). Cultivation of large informal gardens and livestock management practices in the catchment and absence of sanitation facilities such as connection of the communities to an established sewer system to enable the proper collection and the treatment of wastewater also affect the concentration of fecal coliform bacteria in river water (Nath 2008; SPREP 2014; ADB and WAF 2016).

Water quality of the Waimanu River

People's perceptions on water quality

Participants revealed that following a heavy rainfall event, the river water has a muddy appearance. This makes the river water unsuitable for domestic, recreational, and cultural usages increasing the misery of the villagers. Participants from the Sawani and Vuniniudrovu villages have also described that increased sedimentation and siltation in the river system resulting from unsustainable land use changes happening in the upstream and midstream sections of the catchment have increased the frequency of flooding during intense rainfall events.

Water quality at the upstream and downstream intakes

The seven water quality parameters were assessed based on their suitability for the specific usages of the river water including drinking water abstraction and support of aquatic life and recreational purposes in accordance with the international water quality guidelines (Table A2 in Appendix A of the Supplementary Materials). Figure 7 depicts the percentage of observations for turbidity, temperature, TSS, OP, and FC parameters at the Waimanu Intake, which had exceeded the maximum permissible limits relating to the three categories of river water usage. River water at the Waimanu Intake was well oxygenated between 2009 and 2020 since the values for DO and BOD remained within the minimum and maximum permissible limits, respectively, for all the three categories of river water usage.

Physical contamination of the river water was evident with substantial exceedances in turbidity and temperature values in terms of drinking water abstraction usage. However, river water sourced for drinking water abstraction was always treated by the WAF at the Tamavua Treatment Plant prior to distribution for human consumption to ensure that the treated water adhered to the drinking water quality guidelines. Furthermore, frequent (57%) exceedances in OP resulted in nutrient pollution which constituted a risk to the survival of aquatic organisms. For recreational purposes, microbial pollution was detected at the Waimanu Intake when values of FC surpassed the maximum limit in almost 50% of the months between 2002 and 2020 which posed health risks to the villagers. The frequency of turbidity, temperature, DO, TSS, OP, and FC parameters at the Waila Intake, which had exceeded the maximum permissible limits over the 11-year period (2010–2020) relevant to the three categories of river water usage, is shown below (Fig. 8). Overall, higher river water temperature, levels of turbidity, and concentrations of TSS and FC along with lower concentration of dissolved oxygen were detected downstream of the Waimanu River.

The values for BOD remained within the maximum permissible limits for all the three categories of river water usage. There were substantial exceedances in turbidity, temperature, and TSS values in terms of drinking water abstraction usage, which resulted in the physical contamination of the downstream river water. However, the raw river water was always treated at the Waila Treatment Plant to ensure that clean and safe drinking water was supplied to the consumers. Aquatic life was threatened by frequent

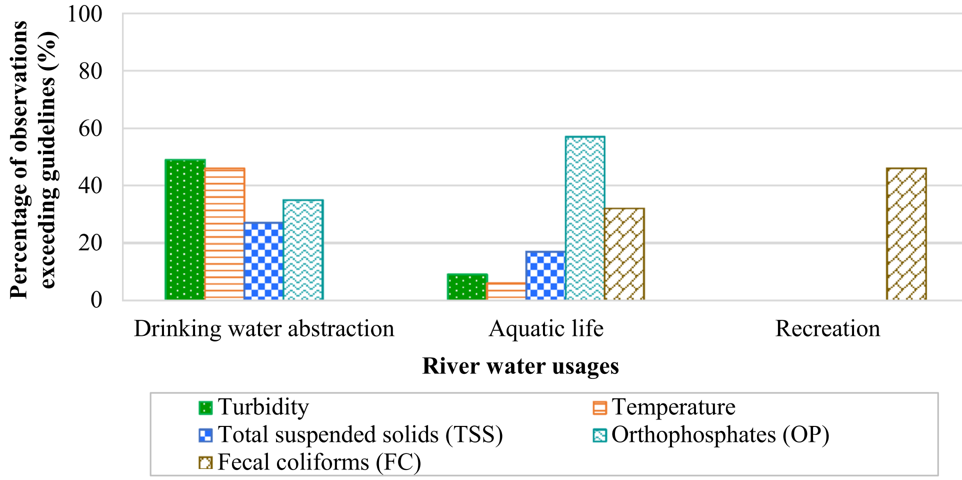

Fig. 7 Frequency of water quality parameters exceeding the water quality criteria for three categories of river water usage at the upstream Waimanu Intake (note: turbidity was assessed using the United States Environmental Protection Agency water quality criteria; temperature, total suspended solids (TSS), and orthophosphates (OP) were assessed based on the European Union and the Organization for Economic Co-operation and Development (EU-OECD) criteria; fecal coliforms (FC) were evaluated based on the EU-OECD criteria for drinking water abstraction and aquatic life maintenance, and the World Health Organization criteria for recreation. The water quality assessment period was 19 years (2002–2020) for turbidity, temperature, and FC; and 12 years (2009–2020) for TSS and OP) (data source: Water Authority of Fiji (2020))

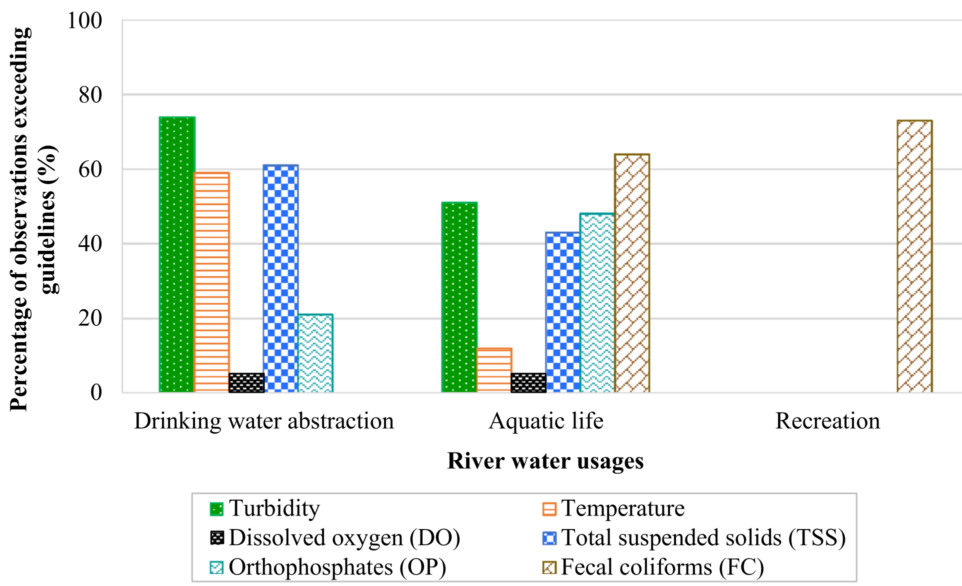

Fig. 8 Frequency of water quality parameters exceeding the water quality criteria for three categories of river water usage at the downstream Waila Intake between 2010 and 2020 (note: turbidity was assessed using the United States Environmental Protection Agency water quality criteria; temperature, total suspended solids (TSS), and orthophosphates (OP) were assessed based on the European Union and the Organization for Economic Co-operation and Development (EU-OECD) criteria; fecal coliforms (FC) were evaluated based on the EU-OECD criteria for drinking water abstraction and aquatic life maintenance, and the World Health Organization criteria for recreation) (data source: Water Authority of Fiji (2020))

exceedances in FC (64%) and turbidity (51%) which led to microbial and nutrient pollution at the Waila Intake. The river water at the Waila Intake was also observed risky for recreational usage since the values of FC exceeded the maximum permissible limit for recreation in 70% of the months between 2010 and 2020.

Impacts of water quality of the Waimanu River

People's perceptions on the impacts on communities

Participants from midstream communities (Sawani and Vuniniudrovu) revealed that due to the contamination of the river water, the population of freshwater fish and *kai* has gradually declined. One of the villagers specified that "following a heavy rainfall or flooding event it becomes difficult for the fishermen to fish in turbid water. This creates greater challenges for households who are contingent entirely on fishing to meet their nutritional and dietary necessities. In all four villages, fishing serves as the second major source of food and income for the households besides earning wages and salaries from employment. Moreover, fishing is also valued for its social, recreational and cultural significance in the Waimanu Catchment." Fishermen from the midstream and downstream communities stated that in order to catch fish, they need to go fishing further upstream of the Waimanu and Rewa rivers. As a result of the long distance, it becomes expensive when the fishermen fuel the boats to go further from their villages. Furthermore, the midstream and downstream communities are less reliant on the river for recreational usage as a result of the pollution in the river water. One of the village headmen mentioned that "all the communities in the Waimanu Catchment have access to piped water from the Suva-Nausori water supply that is, treated at Waila therefore, they do not have to depend solely on the river water to meet their water needs as the river water no longer seems safe to use for swimming, bathing, washing, cleaning, cooking and agricultural purposes."

Effects of declining river water quality on water utilities, freshwater organisms, and people's health

Excessive rainfall in the wet season accelerates the flow of debris in the river causing blockage at the water intakes. This delays the water pumping process and the WAF deploys its divers who risk their lives while attempting to clear these blockages. Frequent intense flooding and erosion at the Waimanu and Waila intakes during the rainy seasons have led to major disruptions to the collection of potable water resulting in an intermittent supply of water to households since the treatment plant systems require emergency repair works following the occurrences of intense rainfall and flood events (Nath 2008; ACP-EU 2018). As a result, there have been frequent water supply shortages and breakdowns which lead to varying operations of the water intakes and treatment plants across the wet and dry seasons.

During periods of severe rainfall events, chlorine dosing rate is increased. Incidences when levels of turbidity, OP, and TSS exceeded the drinking water abstraction criteria at the intakes over the study period and the filtration capacities of the Tamavua and Waila water treatment plants were burdened. High levels of turbidity in the river water overloaded the clarifiers necessitating increased dosage of coagulant. Therefore, low turbidity in the raw untreated water is mandatory to enable effective disinfection (MoH 2005). The processing and treatment of more polluted water sourced from the Waimanu River is prolonged and expensive in ensuring cleanliness and safety for consumption which consequently delays the supply of treated water (ACP-EU 2018; JICA et al. 2020; WAF 2021). The loss of electricity is also a typical issue during the wet cyclone season attributed to the occurrence of natural disasters, which further impedes the treatment process and causes interruptions in the supply of treated water to customers.

Increased concentration of TSS into the river water destroys the habitats of aquatic organisms, which decreases the availability of freshwater fish and invertebrates such as *kai*, mussels, and eels in the river (Mosley et al. 2004a, b; SPREP 2014). A major decline in the production of *kai* was observed between 1992 and 1993 ascribed to the extreme flooding during the occurrence of Tropical Cyclone Kina (ADB and WAF 2016). Furthermore, microbial pollution poses health risks to people. Higher concentrations of FC in the river water increase risks of diarrhea and urinary tract infection to people who consume the polluted fish and *kai* from the river (Naqasima 1996; WHO 2008; Waqalevu 2015). Moreover, when whole-body contact is made with recreational waters through bathing, swimming, and fishing, the risk of swallowing water exists (WHO 2021). Ingestion may result in gastrointestinal infection whereas bodily contact could lead to skin, eye, or wound infections (WHO 2017).

The need for an integrated approach

When exploring the water quality of a river, it is vital to consider both climatic and non-climatic factors affecting the river system since non-climatic factors could be controlled (Begg et al. 2021) to ameliorate the river water quality in a catchment and subsequently, to limit the adverse impacts of poor water quality on the dependent communities. Land use assessment on a catchment scale is essential to determine the location of stressors in the catchment which contribute to the deterioration of the river water quality. The evaluation of climate variables such as rainfall is also important to determine its role in exacerbating the quality of the river water. Similarly, a water quality assessment assists in evaluating the suitability of the river water for various uses, and to ascertain the vulnerability of communities which depend on the river water. The water quality assessment also helps in identifying the contaminants in the river water and detecting the sources of the contaminants on land which require rectification. Therefore, employing an integrated approach helps to comprehend the impacts of climate-related hazards including rainfall and flooding along with the land use patterns on the river water quality at a catchment scale, and to assess the impacts of the water quality on communities which are dependent on the river system. Using a mixed-method approach provides a more comprehensive representation of the vulnerability of riverine communities (Begg et al. 2021) to river water pollution in a catchment area as the scale of vulnerability differs across communities depending on their proximity to the river and to the environmental stressors. Moreover, capturing the perceptions of people residing within a catchment is crucial for future policymaking in addition to conducting quantitative assessments.

Effects of rainfall and land use practices in the Waimanu Catchment

Land use activities including deforestation, logging, gravel extraction, poor agricultural practices, and improper waste disposal from the households and timber sawmill deteriorated the water quality of the Waimanu River by producing increased runoffs, causing erosion, sedimentation, siltation and pollution. Hence, the water quality of the river remained poor even during the non-rainy or lower rainfall days since the water quality parameters still exceeded the river water quality guidelines. When excessive rainfall occurred, sewage runoff or seepage into the river was almost certain as a consequence of improper sewage disposal including leaking septic tanks. The second major concern was runoffs from agricultural farms such as chemical fertilizers, herbicides, weedicides, pesticides, and animal effluents (Nath 2008; SPREP 2014).

The impacts of heavy rainfall and flooding on the river water quality were more perilous than the physical effects of flooding. This is because even after the rainfall and flood events were over, the contaminants remained in the river system. These contaminants originated from land use activities happening within the catchment area, and rainfall amplified the impacts of land use practices on the water quality by accelerating the runoff rate of contaminants into the already contaminated river system.

The water quality data presented in this study agree with other research on water quality in Fiji such as the Rewa Catchment also situated in Nausori, Fiji. The 8-year historical analyses (2005–2012) of the water quality data at the Rewa river mouth located in the Rewa Delta, which is far downstream of our study area, showed moderate levels of nutrients and fecal coliforms sourced from agricultural farms and improper sewage disposal in the catchment area (SPREP 2014; ADB and WAF 2016). These hindered the usability of the Rewa River for drinking water abstraction, recreation, and maintenance of aquatic life. Conversely, pristine rivers in the Nakorotubu watershed in Viti Levu showed optimum water quality parameters such as water temperature of 22 to 26 °C, DO levels above 70% and very little turbidity ascribed to the intact forest cover in the upper and middle watershed portions (Boseto 2009).

Implications of future climate change and land use changes on river water quality in Fiji

It is projected that air and sea temperature increases leading to higher precipitation and extreme weather events will continue to impact the Pacific Islands (IPCC 2021). Cloud bands will also become thicker and wider (Douville et al. 2021). Future climate change projections indicate that heavy rainfall associated with tropical cyclones and flooding events are expected to become more intense and frequent (BoM and CSIRO 2014; Brown et al. 2017; GoF 2018; Douville et al. 2021). River water quality is expected to deteriorate to a poorer quality in future assuming the predicted impacts of climate change (Douville et al. 2021). These would adversely affect freshwater ecosystems and constitute greater health risks to the Pacific Islanders who depend on the river water for subsistence, livelihoods, and recreation purposes (Hills et al. 2011; SPC et al. 2012; Garg et al. 2018; GoF 2018).

Land use activities such as deforestation, agriculture, commercial activities, and improper waste management are likely to increase runoffs containing contaminants into the river systems, subsequently triggering physicochemical and microbial pollution (Douville et al. 2021). Greater nutrient and microbial loadings would cause oxygen depletion which could consequently lower the levels of DO in the river below the minimum permissible limits essential for the survival of aquatic organisms and drinking water abstraction (Mosley et al. 2004a, b; SPREP 2014). The level of DO is affected by variations in other environmental factors such as the river water temperature (Chen and Lu 2014; Irby et al. 2018). Water temperature is most sensitive to the intensity of rainfall and climate change scenarios (Sinokrot and Gulliver 2000; Chen and Lu 2014; Altieri and Gedan 2015; Irby et al. 2018) whereas turbidity, TSS, FC, and OP are more sensitive to land use practices (Edwards and Withers 2008; Bu et al. 2014; Chen and Lu 2014; de Andrade Costa et al. 2020; Santy et al. 2020). Increased concentrations of TSS, FC, and OP in the river increase the turbidity which is the most visible, rapid, and immediate effect of heavy rainfall events on the river water quality (WHO 2017).

The frequency of occurrence of heavy rainfall events is expected to increase by approximately 20 to 40% when future climate El Niño events occur in Fiji (Chand et al. 2017) and according to the baseline information and climate change projections for the Waimanu Catchment, more frequent and intense flooding is expected in the lower catchment area (ADB and WAF 2016). Moreover, physicochemical and microbial pollution in the Waimanu River is expected to intensify as the river flows downstream with more land use activities (gravel quarry, agricultural, and sawmill) and communities concentrated in the middle and lower portions of the river (Fig. 2). These would overburden the filtration capacity of the water treatment plants and require more chlorination (disinfection) to treat the contaminated raw water. Accordingly, the water utility would need to strategize and increase investment in better infrastructure to support efficient water quality monitoring and treatment to be able to supply a better water quality to their customers.

The interconnectedness within the catchment

People settled close to the Waimanu River as it was essential to their existence but gradually, the river system was unable to provide the services as it did earlier. Nonetheless, people remained situated next to the river deprived of their subsistence, livelihood, and recreational necessities. Since the usual source of protein had declined, people started depending on processed foods which increased the risk of noncommunicable diseases. The households situated in the four riverine villagers typically had a low-income status. This was ascribed to the high population of less mobile and dependent groups including children and the elderly (Begg et al. 2021). While external employment in government and private sectors was the primary source of income for the households and subsistence activities such as farming and fishing served as the secondary sources of livelihoods. Hence, when the households spent most of their already small income on processed foods, they had hardly any savings to finance the education of their children and health services which intensified their vulnerability to social, environmental, economic, and climatic shocks. The impacts were not only in the physical context but also in terms of the deterioration of the river water quality and the loss of connections with people.

While increased intensity of rainfall was experienced throughout the catchment, the impacts of flooding and land use activities were confined in nature (Begg et al. 2021). Upstream-midstream-downstream associations substantially determine the vulnerability of communities to water pollution within a catchment because land use practices which instigated river water contamination in midstream (Sawani and Vuniniudrovu) and downstream (Navuso) communities were undertaken within midstream as well as in upstream (Navatuvula) communities.

Therefore, to regulate the river water quality and flooding issues, controlling land use practices upstream is just as important as managing the physical effects of flooding in downstream communities. The results of this study accentuate land management in upstream and midstream communities to reduce the adverse impacts on the river water quality in both midstream and downstream communities. The land management actions entail the inclusion of local residents and landowners throughout the catchment in addition to the organizations involved in undertaking the land use activities in the catchment. Furthermore, flood mitigation actions should combine risks of future rainfall and land use evolutions to analyze how future rain and floodwaters would transport the contaminants originating from land use activities into the river water which the river system will bring down to the communities.

The restoration and management of natural resources such as forests throughout a catchment area are paramount for the sustainability of rivers (GEF et al. 2007; Boseto 2009). Thus, execution of better land management along with the provision of proper sanitation and waste management services in rural catchment areas would prove to be a means to improve the quality of river water worldwide (DeFries and Eshleman 2004; Nilsson and Renöfält 2008; Boseto 2009; Pattison and Lane 2012; Tornevi et al. 2014; de Andrade Costa et al. 2020; Santy et al. 2020; Singh and Railoa 2020).

Research and knowledge gaps

The water quality framework employed in this study to evaluate the physicochemical and microbiological status of the Waimanu River is applicable in a global context to regulate water catchment management strategies in controlling the deterioration of the river water quality. Several studies in other countries employed either locally or globally accepted water quality standards to detect the incidences of physicochemical and microbial pollution in rivers and to assess the suitability of the river water quality for ecosystem sustainability and human usage (Mosley and Aalbersberg 2003; Gholami and Srikantaswamy 2009; Zeb et al. 2011; Heaney et al. 2015; de Andrade Costa et al. 2020). Analyzing the upstream to downstream connections within a catchment area helps in assessing the vulnerabilities of downstream communities (Begg et al. 2021) to river water pollution caused by environmental changes, which in turn assists in the water resource management in countries throughout the world.

Rivers in the high islands of the Pacific serve as major sources of drinking water, subsistence, livelihoods, and recreation. Thus, international water quality guidelines are used locally and regionally to monitor the appropriateness of the river water for various usages. The findings in this study can be generalized to other rural water catchment areas with similar features particularly in developing countries which undergo continuous landscape changes and are also susceptible to the risks from climate change. This requires better water quality monitoring methods to effectively track the consequent variations in the river water quality (Mirti and Davies 2005; Singh and Railoa 2020).

Our study, using monthly sampling and globally accepted standards of assessing water quality, serves to identify the main factors influencing water quality in a typical Pacific Island River system. However, an exhaustive exploration of the spatial variations in the river water quality using the Geographic Information System spatial analyst tool and the Soil and Water Assessment Tool (SWAT) model similar to Chen and Lu (2014) could help to explicate the effects of land use changes on the river water quality.

Sampling the river water on a monthly basis due to the lack of resources in Pacific Island municipalities is insufficient in providing a comprehensive foundation for an effective water management plan (Mosley et al. 2004a, b; Singh and Railoa 2020). The lack of water quality data in the Pacific Islands curtails a detailed understanding of the issues pertaining to the decline in river water quality, which in turn hinders the implementation of appropriate holistic water catchment management plans (Mosley et al. 2004a, b; Boseto 2009).

Conclusions

In this study, both the qualitative and quantitative water quality assessments of the Waimanu River provided convincing evidence of the extent of physicochemical and microbial pollution in the river, the factors driving it, and the time variation of such pollution. Eventually, the river was unable to provide water, food, income, and recreation services to the communities which augmented the vulnerability of the villagers to water pollution. The treatment of polluted water sourced from the Waimanu River was prolonged and expensive which consequently delayed the supply of treated water to customers. Both climatic and non-climatic factors affect the river system; however, only non-climatic factors could be controlled to ameliorate the river water quality in a catchment to limit the adverse impacts of poor water quality on the dependent communities. Frequent rainfall events intensified the runoff into the river system of contaminants such as fertilizer, herbicides, weedicides, pesticides, livestock waste, leaking human sewage, and eroded soil arising from unsustainable land use practices in the Waimanu Catchment including agriculture, gravel extraction, logging, deforestation, and improper waste management. The projected increase in the frequency of more intense wet weather events would probably deteriorate the river water quality further posing bigger challenges for the riverine communities as well as for the drinking water producers. This necessitates better land management policies and provision of sanitation facilities to regulate proper waste management in the Waimanu Catchment so as to enhance the river water quality downstream since flows of water and the levels of contaminants causing water pollution initiate upstream. In order to promote human health and to build resilience to the impacts of environmental factors in riverine communities, river water quality could be monitored and maintained in different regions of the world using the rainfall variability, land use, and water quality assessment methodologies similar to that employed in this study.

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Declarations

Consent to participate The researcher obtained respective informed consent from the village heads and participants prior to conducting the focus group discussions in the field.

Conflict of interest The authors declare no competing interests.

References

Abou Rafee SA, de Freitas ED, Martins JA, Machado CB, Uvo CB (2021) Hydrologic response to large-scale land use and cover changes in the upper Paraná River Basin between 1985 and 2015. Reg Environ Change 21:1–14. https://doi.org/10.1007/s10113-021-01827-6

ADB (2013) The economics of climate change in the Pacific. Asian Development Bank, Mandaluyong. https://www.adb.org/sites/default/files/publication/31136/economics-climate-change-pacific.pdf. Accessed on 2 March 2021

ADB, WAF (2016) Fiji: urban water supply and wastewater management project, Rewa River water supply subproject (Environmental Assessment Project No. 49001–002). Asian Development Bank, Suva. https://www.adb.org/sites/default/files/linked-documents/49001-002-ieeab.pdf. Accessed on 2 May 2021

African, Caribbean and Pacific-European Union (ACP-EU) (2018) Baseline assessment of development minerals in Fiji. United Nations Development Programme, Suva. https://www.spc.int/updates/news/2019/03/development-minerals-report-will-help-guide-sustainable-use-of-fijis. Accessed on 7 June 2021

Ahearn DS, Sheibley RW, Dahlgren RA, Anderson M, Johnson J, et al. (2005) Land use and land cover influence on water quality in the last free-flowing river draining the western Sierra Nevada, California. J Hydrol 313:234–247. https://doi.org/10.1016/j.jhydrol.2005.02.038

Altieri AH, Gedan KB (2015) Climate change and dead zones. Glob Change Biol 21:1395–1406. https://doi.org/10.1111/gcb.12754

Atherton J, Olson D, Farley L, Qauqau I (2005) Fiji watersheds at risk: watershed assessment for healthy reefs and fisheries (Final Report to the United States Department of State OESI Grant# SFJ600, 4). Wildlife Conservation Society, Suva. https://fiji.wcs.org/Portals/82/2005_Atherton_Fiji%20watersheds%20at%20risk-%20Watershed%20assessment%20for%20healthy%20reefs%20and%20fisheries.pdf. Accessed on 5 May 2021

Barros AP (2013) Orographic precipitation, freshwater resources, and climate vulnerabilities in mountainous regions. In: Pielke RA (ed) Climate vulnerability: understanding and addressing threats to essential resources. Elsevier, pp 57–78. https://doi.org/10.1016/B978-0-12-384703-4.00504-9. Accessed on 31 May 2021

Begg SS, De Ramon NA, Iese V (2021) Integrated flood vulnerability assessment of villages in the Waimanu River Catchment in the South Pacific: the case of Viti Levu, Fiji. Reg Environ Change 21:83. https://doi.org/10.1007/s10113-021-01824-9

BoM, CSIRO (2014) Climate variability, extremes and change in the Western Tropical Pacific: new science and updated country reports (Pacific-Australia Climate Change Science and Adaptation Planning program technical report). Australian Bureau of Meteorology and Commonwealth Scientific and Industrial Research Organization, Melbourne. https://www.pacificclimatechangescience.org/wp-content/uploads/2014/07/PACCSAP_CountryReports2014_WEB_140710.pdf. Accessed on 20 May 2021

Boseto D (2009) Freshwater fish and water quality of two catchments in the Nakorotubu Range, Ra and Tailevu Provinces, Viti Levu, Fiji. In: Morrison C, Nawadra S, Tuiwawa M (eds) A rapid biodiversity assessment of the Nakorotubu Range, Ra and Tailevu Provinces, Fiji. Conservation International, pp 63–67. https://doi.org/10.1896/054.059.0110. Accessed on 2 July 2021

Brown P, Daigneault A, Gawith D (2017) Climate change and the economic impacts of flooding on Fiji. Climate Dev 9:493–504. https://doi.org/10.1080/17565529.2016.1174656

Bu H, Meng W, Zhang Y, Wan J (2014) Relationships between land use patterns and water quality in the Taizi River basin, China. Ecol Ind 41:187–197. https://doi.org/10.1016/j.ecolind.2014.02.003

Byamukama D, Kansiime F, Mach RL, Farnleitner AH (2000) Determination of Escherichia coli contamination with chromocult coliform agar showed a high level of discrimination efficiency for differing fecal pollution levels in tropical waters of Kampala, Uganda. Appl Environ Microbiol 66:864. https://doi.org/10.1128/aem.66.2.864-868.2000

Carpenter C, Jones P (2004) An overview of integrated water resources management in Pacific Island countries: a national and regional assessment (SOPAC Miscellaneous Report No. 554). South Pacific Applied Geoscience Commission, Suva. http://www.pacificwater.org/userfiles/file/MR0554.pdf. Accessed on 30 June 2021

Chand SS, Dowdy A, Bell S, Tory K (2020) A review of South Pacific tropical cyclones: impacts of natural climate variability and climate change. Climate Change and Impacts in the Pacific 251–273https://doi.org/10.1007/978-3-030-32878-8_6

Chand SS, Tory KJ, Ye H, Walsh KJ (2017) Projected increase in El Niño-driven tropical cyclone frequency in the Pacific. Nat Clim Chang 7:123. https://doi.org/10.1038/nclimate3181

Chang H (2008) Spatial analysis of water quality trends in the Han River basin, South Korea. Water Res 42:3285–3304. https://doi.org/10.1016/j.watres.2008.04.006

Chen J, Lu J (2014) Effects of land use, topography and socio-economic factors on river water quality in a mountainous watershed with intensive agricultural production in East China. PLoS ONE 9:e102714. https://doi.org/10.1371/journal.pone.0102714

Connell J (2015) Vulnerable islands: climate change, tectonic change, and changing livelihoods in the Western Pacific. Contemp Pac 27:1–36. https://doi.org/10.1353/cp.2015.0014

de Andrade CD, de Azevedo JPS, Dos Santos MA, Assumpção RDSFV (2020) Water quality assessment based on multivariate statistics and water quality index of a strategic river in the Brazilian Atlantic Forest. Sci Rep 10:1–13. https://doi.org/10.1038/s41598-020-78563-0

DeFries R, Eshleman KN (2004) Land-use change and hydrologic processes: a major focus for the future. Hydrol Process 18:2183–2186. https://doi.org/10.1002/hyp.5584

Delpla I, Jung AV, Baures E, Clement M, Thomas O (2009) Impacts of climate change on surface water quality in relation to drinking water production. Environ Int 35:1225–1233. https://doi.org/10.1016/j.envint.2009.07.001

Department of Environment (DoE) (2020) National biodiversity strategy and action plan for Fiji 2020–2025. Government of Fiji, Suva. https://www.mowe.gov.fj/wp-content/uploads/2020/06/National-Biodiversity-Strategy-Action-Plan.pdf. Accessed on 12 June 2021

Douville H, Raghavan K, Renwick J, Allan RP, Arias PA, Barlow M, Cerezo-Mota R, Cherchi A, Gan TY, Gergis J, Jiang D, Khan A, Pokam Mba W, Rosenfeld D, Tierney J, Zolina O (2021) Water Cycle Changes. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds) Climate change 2021: the physical science basis. contribution of working group i to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, In Press, pp 1871–2149. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf. Accessed on 12 September 2021

Dudgeon D, Arthington AH, Gessner MO, Kawabata ZI, Knowler DJ, et al. (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. Biol Rev 81:163–182. https://doi.org/10.1017/S1464793105006950

Edwards AC, Withers PJA (2008) Transport and delivery of suspended solids, nitrogen and phosphorus from various sources to freshwaters in the UK. J Hydrol 350:144–153. https://doi.org/10.1016/j.jhydrol.2007.10.053

Emanuel WR, Shugart HH, Stevenson MP (1985) Climatic change and the broad-scale distribution of terrestrial ecosystem complexes. Clim Change 7:29–43. https://doi.org/10.1007/BF00139439

European Union (EU) (1989) European Communities (Quality of surface water intended for the abstraction of drinking water) Regulations, 1989 (S.I. No 294 of 1989. 5). electronic Irish Statute Book (eISB), Government of Ireland. http://www.irishstatutebook.ie/eli/1989/si/294/made/en/print. Accessed on 15 March 2021

Fan M, Shibata H (2015) Simulation of watershed hydrology and stream water quality under land use and climate change scenarios in Teshio River watershed, northern Japan. Ecol Ind 50:79–89. https://doi.org/10.1016/j.ecolind.2014.11.003

Fazey I, Kesby M, Evely A, Latham I, Wagatora D, et al. (2010) A three-tiered approach to participatory vulnerability assessment in the Solomon Islands. Glob Environ Chang 20:713–728. https://doi.org/10.1016/j.gloenvcha.2010.04.011

Ferguson CM, Coote BG, Ashbolt NJ, Stevenson IM (1996) Relationships between indicators, pathogens and water quality in an estuarine system. Water Res 30:2045–2054. https://doi.org/10.1016/0043-1354(96)00079-6

Fewtrell L, Bartram J (2001) Water quality guidelines, standards and health: assessment of risk management for water-related infectious disease. IWA Publishing, London. https://apps.who.int/iris/bitstream/handle/10665/42442/924154533X.pdf?sequence=1. Accessed on 8 March 2021

FMS (2017) TC Ella expected to track further to the north of Vanua Levu. Fiji Meteorological Service, Nadi. https://www.met.gov.fj/aifs_prods/Media%20Releases/Media_13_May.pdf. Accessed on 23 March 2022

FMS (2020) 2020/2021 Tropical cyclone outlook - "near average to below average cyclone season". Fiji Meteorological Service, Nadi. https://reliefweb.int/report/fiji/fiji-meteorological-service-20202021-tropical-cyclone-outlook-near-average-below-average. Accessed on 8 March 2021

Garg T, Hamilton SE, Hochard JP, Kresch EP, Talbot J (2018) (Not so) gently down the stream: river pollution and health in Indonesia. J Environ Econ Manag 92:35–53. https://doi.org/10.1016/j.jeem.2018.08.011

GEF, UNDP, SOPAC, UNEP (2007) Sustainable integrated water resources and wastewater management in Pacific Island Countries: national integrated water resource management diagnostic report Fiji Islands. South Pacific Applied Geoscience Commission, Suva.

https://www.sprep.org/att/IRC/eCOPIES/Countries/Fiji/49.pdf. Accessed on 12 July 2021
Genkai-Kato M, Carpenter SR (2005) Eutrophication due to phosphorus recycling in relation to lake morphometry, temperature, and macrophytes. Ecology 86:210–219. https://doi.org/10.1890/03-0545
Gholami S, Srikantaswamy S (2009) Statistical multivariate analysis in the assessment of river water quality in the vicinity of KRS Dam, Karnataka, India. Nat Resour Res 18:235–247. https://doi.org/10.1007/s11053-009-9096-y
GoF (2018) Climate vulnerability assessment: making Fiji climate resilient. Government of Fiji, Suva. https://cop23.com.fj/wp-content/uploads/2018/02/Fiji-Climate-Vulnerability-Assessment-.pdf. Accessed on 12 June 2021
Heaney CD, Myers K, Wing S, Hall D, Baron D, Stewart JR (2015) Source tracking swine fecal waste in surface water proximal to swine concentrated animal feeding operations. Sci Total Environ 511: 676–683. https://doi.org/10.1016/j.scitotenv.2014.12.062
Hills T, Brooks A, Atherton J, Rao N, James R (2011) Pacific Island biodiversity, ecosystems, and climate change adaptation: building on nature's resilience. Secretariat of the Pacific Regional Environment Programme, Apia. https://www.sprep.org/attachments/Publications/000931_PIBioEcoCCAdaptation.pdf. Accessed on 11 April 2021
IPCC (2021) Summary for Policymakers. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds) Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, In Press, pp 1–42. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf. Accessed on 12 September 2021
Irby ID, Friedrichs MA, Da F, Hinson KE (2018) The competing impacts of climate change and nutrient reductions on dissolved oxygen in Chesapeake Bay. Biogeosciences 15:2649–2668. https://doi.org/10.5194/bg-15-2649-2018
Jarvie HP, Neal C, Withers PJ (2006) Sewage-effluent phosphorus: a greater risk to river eutrophication than agricultural phosphorus? Sci Total Environ 360:246–253. https://doi.org/10.1016/j.scitotenv.2005.08.038
JICA, Fiji Ministry of Agriculture, Fisheries and Forests (1998) The study of watershed management and flood control for the four major Viti Levu rivers in the Republic of Fiji Islands. Yachiyo Engineering Co., Ltd, Suva. https://openjicareport.jica.go.jp/pdf/11463494_01.pdf. Accessed on 5 April 2021
JICA, Fiji Ministry of Infrastructure, Transport, Disaster Management and Meteorological Services, WAF (2020) Data collection survey for water supply and wastewater sector in the Republic of Fiji. Yachiyo Engineering Co., Ltd, Suva. https://openjicareport.jica.go.jp/pdf/12355251.pdf. Accessed on 1 June 2021
Kistemann T, Claßen T, Koch C, Dangendorf F, Fischeder R, et al. (2002) Microbial load of drinking water reservoir tributaries during extreme rainfall and runoff. Appl Environ Microbiol 68:2188. https://doi.org/10.1128/AEM.68.5.2188-2197.2002
Lako J, Kuridrani N, Sobey M (2019) Freshwater mussel (Batissa violacea) fishery and its value in Fiji. J Pac Stud 39: 192–215. https://doi.org/10.33318/jpacs.2019.39(1)-08
Lata S, Nunn P (2012) Misperceptions of climate-change risk as barriers to climate-change adaptation: a case study from the Rewa Delta, Fiji. Clim Change 110:169–186. https://doi.org/10.1007/s10584-011-0062-4
Lavrakas PJ (2008) Encyclopedia of survey research methods. Sage Publications, Californiahttps://doi.org/10.4135/9781412963947
Lebek K, Senf C, Frantz D, Monteiro JA, Krueger T (2019) Interdependent effects of climate variability and forest cover change on streamflow dynamics: a case study in the upper Umvoti River Basin, South Africa. Reg Environ Change 19:1963–1971. https://doi.org/10.1007/s10113-019-01521-8
Mirti AV, Davies S (2005) Drinking water quality in the Pacific Island countries: situation analysis and needs assessment. South Pacific Applied Geoscience Commission, Suva. https://pacificdata.org/data/dataset/drinking-water-quality-in-the-pacific-island-countries-situation-analysis-and-needs-assessment. Accessed on 21 March 2021
MoH (2005) Fiji national drinking water quality standards. Ministry of Health, Suva.
Morrison RJ, Clarke WC (1990) Soil erosion in Fiji-problems and perspectives. J Japan Soc Eros Control Eng 43: 52–59. https://doi.org/10.11475/sabo1973.43.2_52
Mosley LM, Aalbersberg WG (2003) Nutrient levels in sea and river water along the 'Coral Coast' of Viti Levu, Fiji. South Pac J Nat Appl Sci 21:35–40. https://doi.org/10.1071/SP03007
Mosley LM, Aalbersberg WG (2005) Nutrient levels and macro-algal outbreaks in Fiji's coastal water (IAS Technical Report No. 2005/01). Institute of Applied Sciences, University of the South Pacific, Suva. https://www.sprep.org/att/IRC/eCOPIES/countries/fiji/68.pdf. Accessed on 31 March 2021
Mosley LM, Sharp DS, Singh S (2004a) Effects of a tropical cyclone on the drinking-water quality of a remote Pacific Island. Disasters 28:405–417. https://doi.org/10.1111/j.0361-3666.2004.00266.x
Mosley LM, Singh S, Aalbersberg B (2004b) Water quality monitoring in Pacific Island Countries (SOPAC technical report 381). South Pacific Applied Geoscience Commission, Suva. https://www.researchgate.net/publication/255700290_Water_quality_monitoring_in_Pacific_Islands. Accessed on 31 March 2021
Mulholland PJ, Houser JN, Maloney KO (2005) Stream diurnal dissolved oxygen profiles as indicators of in-stream metabolism and disturbance effects: Fort Benning as a case study. Ecol Ind 5:243–252. https://doi.org/10.1016/j.ecolind.2005.03.004
Naqasima M (1996) An investigation of public health and fisheries issues concerning Anadara antiquata (Mollusca, Bivalvia: Arcidae) and Batissa violacea (Bivalvia: Corbiculacea). Dissertation, University of the South Pacific
Nath D (2008) Waila water safety plan. Fiji Water and Sewerage Department, Suva. http://www.pacificwater.org/userfiles/file/Waila%20Water%20Safety%20Plan.pdf. Accessed on 5 March 2021
Nausori Town Council (2012) Weather and climate. Nausori Town Council, Nausori. http://nausoritowncouncil.org/weather-climate/. Accessed on 7 March 2021
Nilsson C, Renöfält BM (2008) Linking flow regime and water quality in rivers: a challenge to adaptive catchment management. Ecology and Society 13: http://www.ecologyandsociety.org/vol13/iss2/art18/
Nobre RLG, Caliman A, Cabral CR, de Carvalho AF, Guerin J, et al. (2020) Precipitation, landscape properties and land use interactively affect water quality of tropical freshwaters. Sci Total Environ 716:137044. https://doi.org/10.1016/j.scitotenv.2020.137044
Nunn PD (2009) Responding to the challenges of climate change in the Pacific Islands: management and technological imperatives. Climate Res 40:211–231. https://doi.org/10.3354/cr00806
OECD (2008) Annex 1 Data sheets for surface water quality standards. OECD Environment Outreach, Paris. https://www.oecd.org/env/outreach/38205662.pdf. Accessed on 20 March 2021
Pattison I, Lane SN (2012) The link between land-use management and fluvial flood risk: a chaotic conception? Prog Phys Geogr 36:72–92. https://doi.org/10.1177/0309133311425398
Puustinen M, Koskiaho J, Peltonen K (2005) Influence of cultivation methods on suspended solids and phosphorus concentrations in

surface runoff on clayey sloped fields in boreal climate. Agr Ecosyst Environ 105:565–579. https://doi.org/10.1016/j.agee.2004.08.005
Raj R (2004) Integrated flood management (case study: Fiji Islands flood management–Rewa river basin). World Meteorological Organization/Global Water Partnership Associated Programme on Flood Management. http://www.floodmanagement.info/publications/casestudies/cs_fiji_full.pdf. Accessed on 28 March 2022
Santy S, Mujumdar P, Bala G (2020) Potential impacts of climate and land use change on the water quality of Ganga River around the industrialized Kanpur region. Sci Rep 10:1–13. https://doi.org/10.1038/s41598-020-66171-x
Shah VG, Dunstan RH, Geary PM, Coombes P, Roberts TK, et al. (2007) Comparisons of water quality parameters from diverse catchments during dry periods and following rain events. Water Res 41:3655–3666. https://doi.org/10.1016/j.watres.2007.02.052
Singh D, Railoa K (2020) Microbial analysis of drinking water from Nadi to Lautoka Area in Viti Levu Fiji. Pacific Health 3. https://doi.org/10.24135/pacifichealth.v3i0.43
Sinokrot BA, Gulliver JS (2000) In-stream flow impact on river water temperatures. J Hydraul Res 38:339–349. https://doi.org/10.1080/00221680009498315
Soil Bureau, Department of Scientific and Industrial Research, New Zealand (1961) Soil Map of Fiji, North-western Viti Levu, Malolo and Southern Lomaiviti (Sheet 5, 1961, 1:126 720). Government of Fiji. https://openresearch-repository.anu.edu.au/handle/1885/186347. Accessed on 21 May 2021
SPC, World Meteorological Organization, United Nations Educational, Scientific and Cultural Organization, European Union (2012) Catalogue of rivers for Pacific Islands. Secretariat of the Pacific Community, Suva. http://pacificwater.org/_resources/article/files/Binder1.pdf. Accessed on 18 April 2021
SPREP (2014) Fiji's State of Environment Report 2013. Secretariat of the Pacific Regional Environment Programme, Apia. http://macbio-pacific.info/wp-content/uploads/2017/08/State-of-Environment-Report-2013.pdf. Accessed on 11 April 2021
Sullivan AB, Snyder DM, Rounds SA (2010) Controls on biochemical oxygen demand in the upper Klamath River, Oregon. Chem Geol 269:12–21. https://doi.org/10.1016/j.chemgeo.2009.08.007
Tappin AD, Comber S, Worsfold PJ (2016) Orthophosphate-P in the nutrient impacted River Taw and its catchment (SW England) between 1990 and 2013. Environ Sci Process Impacts 18:690–705. https://doi.org/10.1039/C6EM00213G
Terry JP, Garimella S, Kostaschuk RA (2002) Rates of floodplain accretion in a tropical island river system impacted by cyclones and large floods. Geomorphology 42:171–182. https://doi.org/10.1016/S0169-555X(01)00084-8
Terry JP, Kostaschuk RA (2004) Extreme river behavior in the Pacific Islands–case studies from Samoa and Fiji. Asia Pacific Association of Hydrology and Water Resources Conference, Singapore. July 5–8
Tornevi A, Bergstedt O, Forsberg B (2014) Precipitation effects on microbial pollution in a river: lag structures and seasonal effect modification. PLoS ONE 9:e98546. https://doi.org/10.1371/journal.pone.0098546
Tuttle-Raycraft S, Ackerman JD (2019) Living the high turbidity life: the effects of total suspended solids, flow, and gill morphology on mussel feeding. Limnol Oceanogr 64:2526–2537. https://doi.org/10.1002/lno.11202
US EPA (1997) EPA guidelines for preparation of the comprehensive state water-quality assessments (305b Reports and Electronic Updates). United States Environmental Protection Agency, Washington DC. https://www.epa.gov/sites/production/files/2015-09/documents/guidelines_for_preparation_of_the_comprehensive_state_water_quality_assessments_305b_reports_and_electronic_updates_1997_volume1.pdf. Accessed on 31 March 2021
US EPA (2021) Environmental Protection Agency, Subchapter D Water Programs. Code of Federal Regulations, Washington DC. https://ecfr.federalregister.gov/current/title-40/chapter-I/subchapter-D/part-131/subpart-D. Accessed on 2 April 2021
Uusitalo R, Yli-Halla M, Turtola E (2000) Suspended soil as a source of potentially bioavailable phosphorus in surface runoff waters from clay soils. Water Res 34:2477–2482. https://doi.org/10.1016/S0043-1354(99)00419-4
Van Aalst MK, Cannon T, Burton I (2008) Community level adaptation to climate change: the potential role of participatory community risk assessment. Glob Environ Chang 18:165–179. https://doi.org/10.1016/j.gloenvcha.2007.06.002
Vunisea A (2004) The challenges of seafood marketing in Fiji. SPC Women in Fisheries Information Bulletin # 14, Nouméa. http://coastfish.spc.int/en/publications/bulletins/women-in-fisheries. Accessed on 21 May 2021
WAF (2021) How heavy rains impact your water supply. YouTube. https://www.youtube.com/watch?v=2M87xpHqFbc. Accessed on 1 July 2021
Waqalevu VP (2015) A preliminary assessment of the human health risks associated with the consumption of the freshwater mussel, Batissa violacea. International Union for Conservation of Nature. Oceania Regional Office (IUCN–ORO). https://www.iucn.org/sites/dev/files/a_preliminary_assessment_of_the_human_health_risks_associated_with_the_consumption_of_the_freshwater_mussel.pdf. Accessed on 24 March 2022
Whitehead PG, Wilby RL, Butterfield D, Wade AJ (2006) Impacts of climate change on in-stream nitrogen in a lowland chalk stream: an appraisal of adaptation strategies. Sci Total Environ 365:260–273. https://doi.org/10.1016/j.scitotenv.2006.02.040
WHO (2008) Guidelines for drinking-water quality, 3rd edn. World Health Organization, Geneva. https://apps.who.int/iris/rest/bitstreams/907844/retrieve. Accessed on 24 March 2022
WHO (2017) Guidelines for drinking-water quality, 4th edn. World Health Organization, Geneva. https://www.who.int/water_sanitation_health/publications/gdwq4-with-add1-chap7.pdf?ua=1. Accessed on 17 October 2021
WHO (2021) Guidelines on recreational water quality. Volume 1: coastal and fresh waters. World Health Organization, Geneva. https://apps.who.int/iris/bitstream/handle/10665/342625/9789240031302-eng.pdf?sequence=1&isAllowed=y. Accessed on 16 October 2021
Wu L, Long TY, Liu X, Guo JS (2012) Impacts of climate and land-use changes on the migration of non-point source nitrogen and phosphorus during rainfall-runoff in the Jialing River Watershed, China. J Hydrol 475:26–41. https://doi.org/10.1016/j.jhydrol.2012.08.022
Zeb BS, Malik AH, Waseem A, Mahmood Q (2011) Water quality assessment of Siran River, Pakistan. International Journal of Physical Sciences 6:7789–7798. https://doi.org/10.5897/IJPS11.1385