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Aquatic contaminants in Solomon Islands and Vanuatu: Evidence from passive samplers and Microtox toxicity assessment

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ABSTRACT

Water Quality issues in many Pacific countries are rising, with the increase in coastal populations and associated urban runoff but management requires contamination issues in the aquatic environment to be identified and prioritised. In Vanuatu and Solomon Islands there are few laboratories and resources to assess for the presence or impact of complex chemical contaminants. The extent and impact of chemical contamination of the marine and coastal environment is poorly described.

Passive chemical samplers were used to measure a range of aquatic pollutants around the capital cities, Honiara (Solomon Islands) and Port Vila (Vanuatu). We detected a range of chemicals indicative of agricultural and industrial contamination and a few sites had concerning concentrations of specific hydrocarbons and pesticides. The rapid ecotoxicology test, Microtox, indicated toxic impacts in rivers, coastal sites and urban drains This work provides new data on chemical contamination and possible impacts of that contamination for both countries. The techniques could be applied widely across the region to generate critical data for environmental management, guide monitoring efforts and measure the impact of policy or land-use changes.

1. Introduction

Vanuatu and Solomon Islands are island nations within the ethnogeographic group of Pacific Islands known as Melanesia, which itself lies within the Oceania region of the Pacific Ocean. Vanuatu is a chain of 13 principal islands along with several smaller islands. The Solomon Islands covers more than two million square kilometres of ocean in a double chain of 922 islands, making it one of the largest archipelagos in the world. Both countries have a rising urban population, which has led to increased input of pollutants into their coastal waters (Graham et al., 2020; Devlin et al., 2020).

This study centres around the two capital cities of Solomon Islands and Vanuatu, as areas with the largest concentrations of people, transport and industry and therefore likely focal points for contamination and pollution (Fig. 1). Port-Vila, the capital of Vanuatu, is located on Éfaté Island and is home to about 45,000 of the island's approximately 84,000 residents. Port Vila is the economic and commercial centre of Vanuatu. Efate is shaped with a large outer bay, Mélé Bay, leading to the smaller Vila bay where most of the boat-based tourism and commercial activity takes place. This inner bay has relatively restricted water changes compared to the parts of the island that face the open Pacific Ocean (Graham et al., 2020). In Solomon Islands, the capital city, Honiara, is on the island of Guadalcanal, with a population of approximately 67,000 in 2019, the only city above 10,000 (worldpopulationreview.com. Accessed June 2019). The population density drops off dramatically outside of the city boundaries. Honiara is situated on the north-western coast and is the biggest concentration of commercial and political activity in the islands (Fig. 2). The high population density in Honiara, concentrated along less than 10 km of coastline and combined with the large amount of boat traffic around Point Cruz seaport, leads to a range of anthropogenic pressures on the coastal and marine environment. Pressures include a lack of sewage treatment facilities, limited litter collection and management, and the concentration of commercial and industrial activity along a relatively small coastal area (Green et al.,

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2006). There are direct impacts on the nearshore coastal waters, but there are also more indirect influences including leachate from mining ponds and unregulated and poorly controlled forestry. These direct and indirect inputs can lead to contamination of drinking water sources and downstream river and estuarine systems (Wenger et al., 2018).

There is a paucity of data from Pacific Island Countries when it comes to chemical contaminants or ecotoxicology in the aquatic environment (Varea et al., 2020; Graves et al., 2020). Pollution control has, however, been identified as one of the pressing concerns in the region (SPREP, 2016) and persistent organic pollutants (POPs) for example, were specifically mentioned as a group of contaminants that are both of concern and lacking in terms of regionally available datasets. Large amounts of land-based POPs waste originally supplied for agricultural purposes, and contaminated soils, were removed across the South Pacific, including in

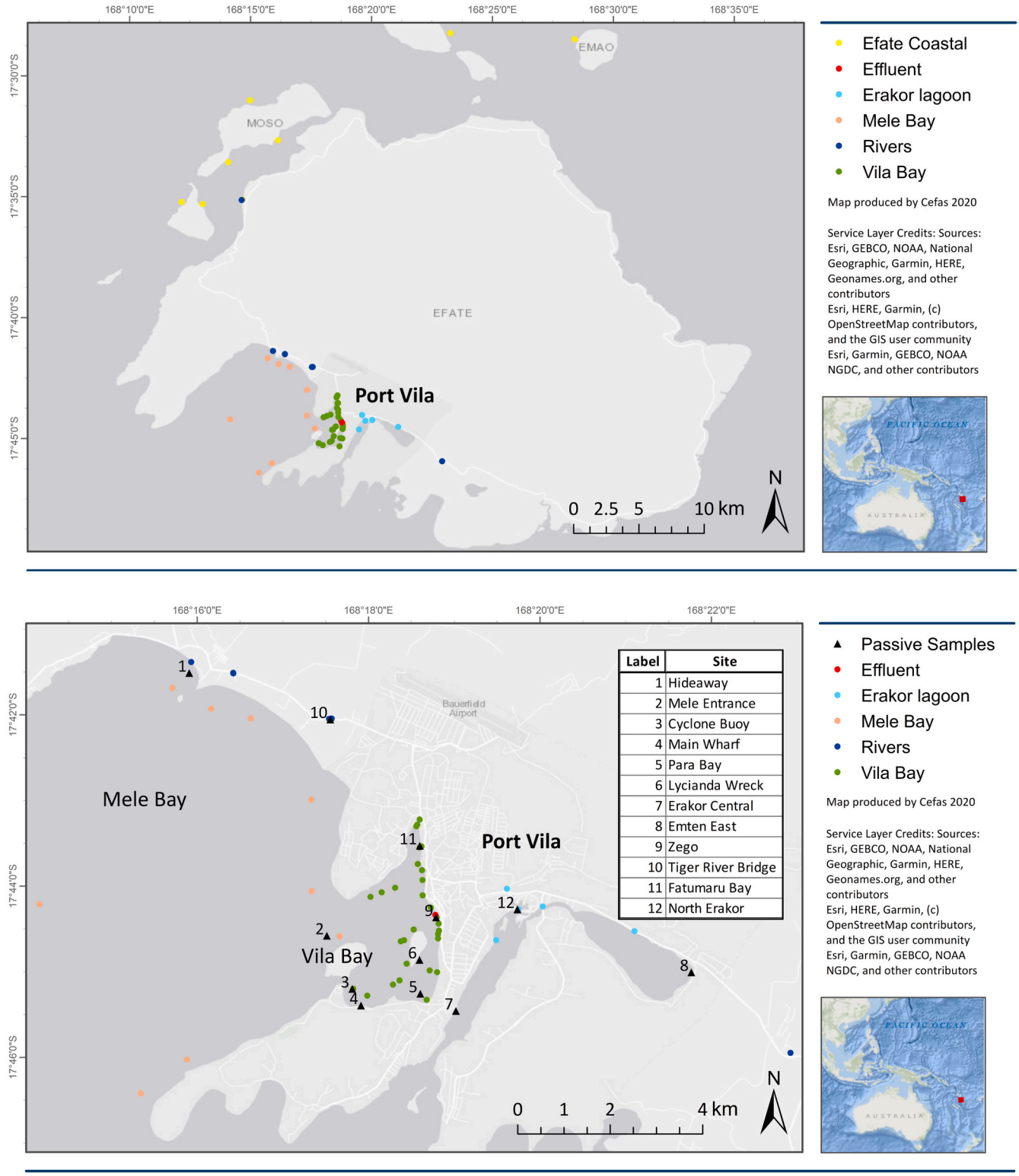

Fig. 1. Site maps for Passive samplers and Microtox analysis in Vanuatu. (top) Efate and surrounding islands. (bottom) Port Vila, Mele Bay and Lagoon areas.

2007 and 2008 from Solomon Islands and Vanuatu (AusAid, 2010). Other regional research has focussed on presence of contaminants in food (e.g. Lal et al., 2014) and there is a building body of research on metals in sediments, mostly focussed around Fiji (Chand et al., 2011; Fujita et al., 2014; Matakite and Singh, 2008; Park et al., 2013; Pratap et al., 2020).

Conducting chemical and biological effects led marine monitoring programmes across small island developing states, such as Solomon Islands and Vanuatu is challenging, due to their geographical remoteness, environmental conditions and lack of in-country analytical

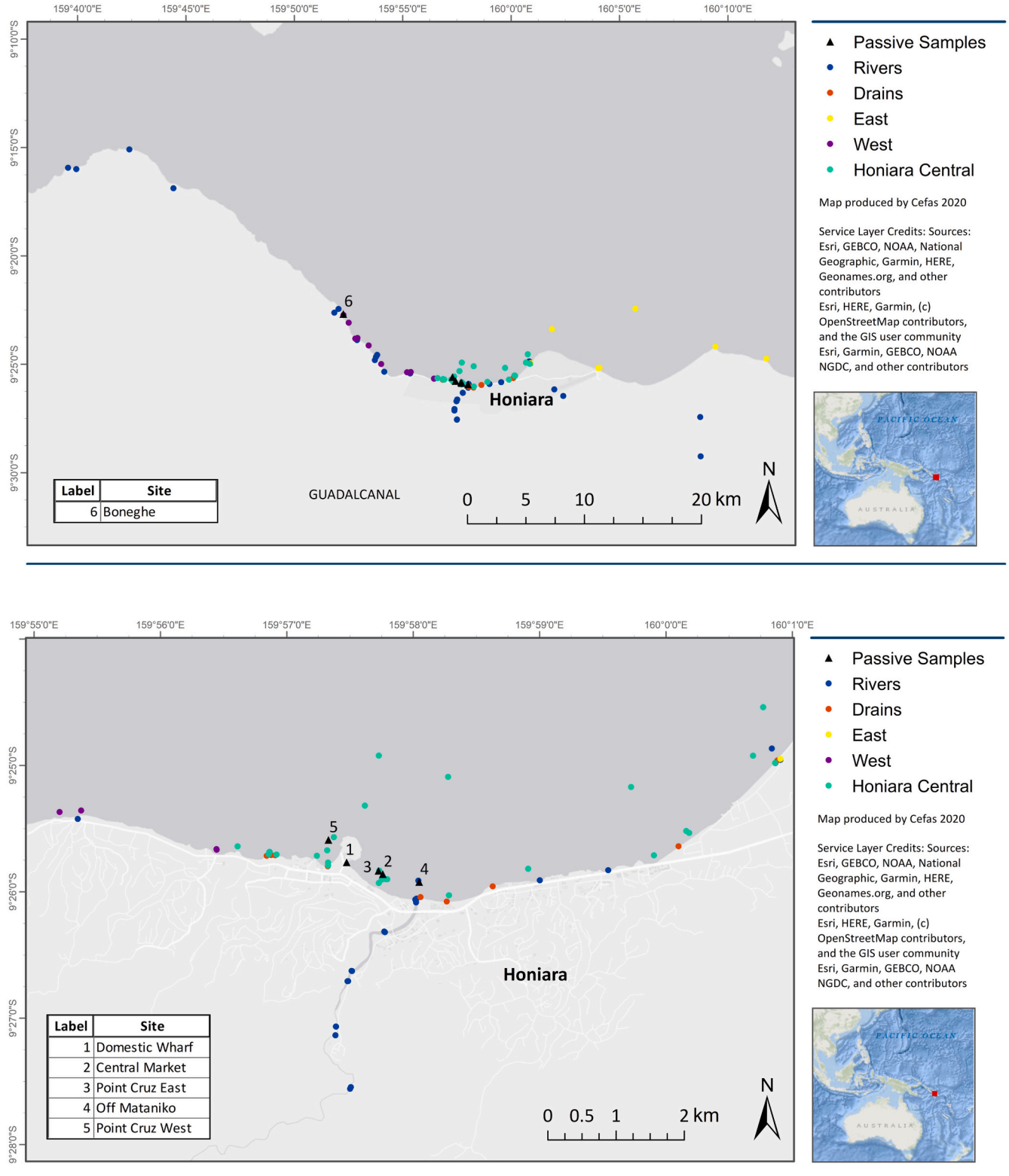

Fig. 2. Site maps for Passive samplers and Microtox analysis in Solomon Islands. (top) North Coast of Guadalcanal showing east and west site locations. (bottom) Central Honiara and Mataniko River sites.

facilities. Traditionally, when conducting chemical pollutant assessment surveys, water is sampled by filling a container at a single point in time. However, samples collected using this approach do not capture the temporal fluctuations in chemical concentrations that may occur at any given location (Raub et al., 2015). Important factors such as fluctuations in water/tidal levels, effluent discharge intervals and rain fall events influence the concentration and variability of chemical pollutants in a water sample. Passive sampling techniques are increasingly employed as an additional approach to chemical sampling in the aquatic environment and an alternative way to measure chemical concentrations (and thus potential exposure) compared to traditional spot sampling (Miège et al., 2015; Booij et al., 2016). Passive samplers deliver time-integrated exposure data (weeks to months) and because only the freely dissolved fraction of the chemical is collected, they provide a measure of the availability of contaminants to organisms. This ability to measure exposure and ease of sampling means passives samplers can be beneficial in monitoring programmes for the assessment of contaminants in both marine and freshwater systems (Larsen et al., 2009; Alvarez, 2010; Bean et al., 2017).

Alongside these analytical chemical approaches, the directed use of biological assays can provide complementary data on the overall risks posed by the mix of chemical contaminant found in any given sample (van der Oost et al., 2003; Thain et al., 2008; Lyons et al., 2010; Wernersson et al., 2015; Vethaak et al., 2017; Khatir et al., 2019). Depending on the type of bioassay employed, biological assays can target contaminants with specific modes of action, such as endocrine disruption chemicals (Thomas et al., 2004; Smith et al., 2015) or be indicative of non-specific toxicity (Thain, 1991; Matthiessen et al., 1993; Eklund, 2005).

The Microtox test is a well-established test measuring the overall toxic impact on the test organism, *Aliivibrio fischeri* as a reliable acute test (Backhaus et al., 1997; Parvez et al., 2006; Wadhia and Thompson, 2007; Colvin et al., 2020). It has been used to detect the impacts of toxic nanoparticles and heavy metals (Aruoja et al., 2015; Yang et al., 2016) various antibiotics (Di Nica et al., 2017; Ji et al., 2013), industrial wastewater and complex leachates (Maselli et al., 2015) and a wide variety of insecticides and pesticides (Gatidou et al., 2015; Mansour et al., 2015).

The use of the assay provides an overall measure of the risk posed by complex mixtures and helps to target sites without any pre-knowledge of what chemical contaminants may be present (van der Oost et al., 2003). In regions with limited baseline information, selecting the right combination of effects directed bioassays and chemical analysis can enhance the capability to monitor for both specific and unknown pollutants and understand how anthropogenic pressures are impacting marine environmental health (Wernersson et al., 2015; Kroon et al., 2019).

Here we present a study that applied a combination of silicone rubber (polydimethylsiloxane, PDMS) passive chemical samples and the Microtox assay to provide simple on-site techniques for sites without easy access to chemical and ecotoxicological laboratories.

Sampling was carried out between 2016 and 2017 in Vanuatu, and 2017–2018 in Solomon Islands. Passive samplers were deployed at a total of 12 sites in Vanuatu and 6 sites in Solomons Islands. Unfiltered water samples for Microtox analysis were taken at 68 sites and 101 sites respectively. Sampling locations for Vanuatu and Solomons are presented in Fig. 1 and details of the sites, sampling and full analytical methods are in the supplementary data spreadsheet and document.

We deployed passive samplers made of silicone rubber to sample contaminants in the aquatic phase for each site (Figs. 1 and 2). Contaminants in the water are taken up into the silicone matrix until their concentration is at equilibrium with the surrounding water. This gives a record of the contaminants that have been in the water column during the sampling period and represents the bioavailable fraction rather than 'total' contaminants. Silicone rubber samplers were prepared and analysed according to standard protocols (Smedes and Booij, 2012). Samplers were pre-extracted with ethyl acetate and methanol and loaded with performance reference compounds (PRCs – 13 non-environmental polychlorinated biphenyls (PCBs)) prior to exposure. Field blank samples from the same preparation batch were taken into the field alongside samples and were subsequently analysed alongside samples to allow calculation of loss of PRCs.

The pre-prepared, silicone sheets were stored in clean amber-glass jars and kept frozen prior to deployment. Thirteen sites in Vanuatu and six in Solomon Islands were accessed using small boats or shore-line deployment where access permitted. Floating structures such as buoys and pontoons were used where available. Docks, sunken ships, and custom-built sub-surface buoys were also used dependant on the location and availability of surrounding structures.

Passive samplers were attached to custom-made stainless-steel frames that supported and separated the silicone sheets whilst in the water. Samplers were deployed for several weeks (39 to 67 days) before retrieval and analysed according to the methods in Balaam et al., 2011.

In brief, the recovered silicone rubber samplers were transferred to the Cefas laboratory, scrubbed clean of fouling organisms and other debris, placed in solvent rinsed glass Soxhlet extraction apparatus and spiked with recovery standards before being 'hot' extracted with acetonitrile:methanol [2:1 v.v].

The cleaned up Soxhlet extract was analysed for a suite of polycyclic aromatic hydrocarbons (PAHs) by gas chromatography–mass spectrometry in electron impact ionization mode (GC–MS) using a 6890 GC coupled to a 5975 MSD (Agilent Technologies, Walbron, Germany. Quantification for PAHs was performed using surrogate standards (Kelly et al., 2000).

Extracts for hexabromocyclododecane (HBCDD) analysis were analysed using ultra performance liquid chromatography (UPLC; Acquity, Waters) tandem mass spectrometry (TQ MS/MS; Xevo TQ MS, Waters). Quantitation for HBCDD and TBBP-A was performed using isotope dilution (Lyons et al., 2015).

PCB, organochlorine pesticide (OCP) and PRC concentrations in silicone rubber samples were determined with an Agilent 7890A GC coupled with 7000 QQQ-MS/MS in positive electron impact mode (ESI+) (Lyons et al., 2015).

Polybrominated diphenyl ether congeners (PBDEs) were determined with a Shimadzu 2010plus GC with TQ8050 QQQ-MS/MS in positive electron impact mode (ESI+).

The laboratory participates annually in the proficiency testing scheme Quasimeme (Quality Assurance of Information for Marine Environmental Monitoring in Europe) exercise DE-13 as external quality assurance.

Loss of PRCs from samples relative to the Field Blank was used to calculate sampling rates according to standard protocols (Smedes and Booij, 2012). Contaminant results are expressed as time-weighted average water concentrations.

Microtox® rapid toxicity detection is an *in vitro* test system. It uses bioluminescent bacteria for the detection of toxicity and is used as a screening system to detect the relative toxicity of environmental samples. It responds to chemicals or combinations of chemicals that are toxic to cells or reduce their speed of replication. The Microtox FX™ test system, previously known as Deltatox®, is designed to operate and test samples in the field under ambient temperatures between 0 and 40 °C.

The method followed for this study was the Modern Water Microtox® B-tox test for low toxicity samples. The test procedure is described in full in the Deltatox® II User's Manual (Modern Water, 2012), and a longer description can be found in the supplementary methods file. Freeze dried cultures of *Aliivibrio fischeri* bacteria are revived and their luminescence is measured. 100 μL of the bacterial culture is then gently mixed with 900 μL of sample and incubated for 15 min. Luminescence is read again at the end and changes are given a nominal % change value compared to the luminescence change measured in the control sample. This procedure provides a single toxicity result for each site indicating whether the overall impact of chemicals at the site is causing significant changes to the expected bacterial response.

Environmental samples tend to contain a mixture of known and unknown chemicals at various concentrations. If the mixture present in the sample has an overall inhibitory effect, leading to less growth of the *A. fischeri* bacteria, then this will lead to reduced luminescence which will be reported as a light loss compared to the control. This can be considered as indicative of inhibition of growth.

Increased luminescence compared to the control is therefore considered to indicate growth stimulation. This can be because additional nutrients in the sample support an increased rate of growth for the bacteria. Stimulated growth might also be seen under conditions of hormesis, where low doses of chemicals have a stimulatory effect rather than the inhibitory effect caused by higher concentrations.

For this study, land-based samples were collected from sites representing riverine, effluent or drainage input to the marine environment. Boats were used to collect near shore and open water sites representing sites of interest and coastal transects. Water samples were collected in sterile 15 mL Falcon tubes and stored in cool boxes with ice packs. They were returned to the on-island Cefas laboratory at the end of each day and analysed immediately.

For the passive sampler work, in Vanuatu, thirteen samplers (Fig. 1) were recovered and analysed between 2016 and 2017. A loss of two samplers occurred, most likely due to deliberate removal by people or loss during heavy weather. The results (Tables 1, 2) indicate higher concentrations of some contaminants such as specific PAHs and pesticides, and large variability in concentrations between sites suggesting localised or temporal differences. For the pesticides, a notable variance is the presence of high levels of dieldrin in Port Vila Bay. This is seen across both years, with higher values in 2016. For other contaminants, there are noticeable differences between years but for operational reasons sites were different each year. Thus, although several samplers were in similar areas, direct year-on-year comparison of the results is not possible. Concentrations of the pesticide ß-HCH are higher in 2017 than 2016 and so are the PAHs methyldibenzothiophene and 1-methylphenanthrene. The pesticide endosulfan sulphate was at detectable concentrations in 2016, but not in 2017 and endosulfan II (beta) was below detectable limits at all sites apart from on one occasion at North Erakor in 2017.

The site near the Lycianda wreck is interesting for the ratios of DDT pesticides, showing a higher proportion of parent product than breakdown product. This suggests that the pesticide use is recent rather than picking up legacy contamination (Jürgens et al., 2016). This site is adjacent to Iririki Island resort, which is marketed as a green, ecotourism island.

For flame retardant contaminants, the highest levels of BDE47 and 66 (both tetra BDEs), and BDE99 and 100 (penta BDEs) were found at the Tiger River site, which is located next to several industrial sites next to the river. BDE47 is known to bio-magnify in the food chain, and BDE congeners 47 and 100 have previously been identified as having endocrine disrupting properties and are frequently detected in humans (Kanaya et al., 2019). The Tiger River site also had some elevated PAH values, notably a high concentration of 1-methylpyrene, which is a known carcinogen (Bendadani et al., 2014). There are a few other elevated PAH values at various sites, but the highest PAH concentrations were found in 2017 when large amounts of naphthalenes were detected close to the Zego pontoon in Vila Bay. Zegos are small boats for tourists with outboard motors, fuelled at the site, so this may reflect operational leakage and refuelling spills. There are also high C3-naphthalenes in the main, commercial, Vila bay sites, around the North East of the bay where various boat docking and maintenance activities take place.

The passive samplers also show detectable levels of PCBs, contaminants associated with a legacy of industrial applications during the last century. In Fatumaru bay, CB44 and CB66 were detected at significantly higher concentrations than all other sites sampled suggesting a local input or legacy sources that are leaking into this embayment. The bay receives flow inputs from a number of sources, so these contaminants may be entering the system some distance upstream from a yet to be identified source.

In the Solomon Islands four samplers were placed in 2017 with two recovered, whilst in 2018/19 six were deployed and four were recovered, one from a control area, Boneghe, which is currently relatively undeveloped. It is the site furthest from the commercial and industrial activities in Honiara. Analytical data for contaminants recovered from the silicone sheet passive samplers can be seen in Tables 3 and 4, with full details found in the supplementary data spreadsheet.

In the 2018/19 deployment, the field control samplers were found to have relatively high PAH values. This had to be factored into the analysis of deployed samplers and may have reduced the apparent PAH concentrations in the deployed samplers. During the collection process an engine fault on the boat led to increased exhaust emissions, which may have been responsible. The concentrations of contaminants recorded from Boneghe were generally the lowest recorded for most determinants. The notable exception to this was for the PAH acenaphthene where, even with the blank correction issues from 2018/19, it still registered the second highest concentration among the six Solomon Islands samplers. Acenaphthene is a pyrogenic PAH and possible sources at Boneghe could be emissions from the logging industry. Heavy logging equipment and certain operational practices, including the burning of waste oil, and fuel and oil contaminated materials, are common across the region.

The site at the Domestic Wharf (2017) has more of the high concentration results than any other site although the corrections applied to 2018/19 PAH values due to the contamination issue in the field control sampler means the true values might actually be higher than could be reported confidently. The sum PAH concentration is high at the 2017 sites, but each individual PAH is relatively low. This suggests a broad range of PAHs from several different sources, rather than one significant input. Most of the other chemicals are at detectable concentrations, but in the low pg L^{-1}.

The sum of DDT pesticide and its metabolites is the most significant set of data for the Solomon Islands. All sites show these high amounts of DDT pesticides present, although at the Boneghe site they are at the lowest levels among the Solomon Islands samplers. The Sum-HCH values are also relatively high at the domestic wharf site.

At the Mataniko and Point Cruz East sites, the calculated concentration of perylene is at least five to six times higher than for the other sites sampled. Perylene is a carcinogenic PAH with a long-debated origin. It could be petrogenic (Jautzy et al., 2015), pyrogenic (Wang et al., 1999), but seems primarily to be diagenitic, in that it originates in sediments fed by both terrestrial and aquatic organic debris (Hanke et al., 2019). The values measured here in low picogramme per litre levels are perhaps not interesting from a pollution impact perspective but may suggest some different sediment processes taking place at these sites. It seems possible that the perylene may derive from the Mataniko and Lungga rivers, and that the hydrodynamics around Point Cruz peninsula prevents the movement of the perylene further west (Graham et al., 2020).

The Microtox ecotoxicology testing was carried out at 68 sites in Vanuatu (Fig. 1, Table 5), and 101 sites in Solomon Islands (Fig. 2, Table 6).

Data from the studies in both Vanuatu and Solomon Islands indicated that for most sites the combined toxicity of all chemicals did not significantly impact light production in the *Aliivibrio* bacteria, which reflects the mainly low chemical concentrations measured using the passive samplers. In Vanuatu although samples from several rivers were unaffected, there was more variability than marine waters and one or two river samples exhibited substantial effects. There were, however, a few sites (Supplementary data spreadsheet) that caused acute impacts in the test. In Port Vila, the most impacted sample caused a 50% reduction in growth and was a site near to the effluent drain by the central market. The other sites with notable impacts were two rivers that discharge into Mele bay, one known to receive effluent from industry, causing a 37% reduction. Unexpectedly, the most northern site, furthest from Port Vila,

Table 1
Chemical analysis data in pg L^{-1} from silicone-sheet passive samplers deployed at various sites in Efate, Vanuatu.

	Vanuatu 2016								Vanuatu 2017				
	Mele Bay	Port Vila Bay					Lagoons		Mele Bay	Port Vila Bay		Lagoons	
	Hideaway	Mele Entrance	Cyclone Buoy	Main Wharf	Para Bay	Lycianda wreck	Erakor Central	Emten East	Tiger River Bridge	Fatumaru Bay	Zego pontoon	North Erakor 1	North Erakor 2
Pesticides in pg L^{-1}													
HCBD	0.227	0.248	0.232	0.322	0.407	<0.084	0.955	<0.12	0.0468	<0.059	<0.030	<0.035	<0.036
HCB	3.47	3.80	5.51	5.06	5.27	6.94	6.31	1.98	2.78	4.68	4.28	2.65	2.96
α-HCH	16.2	14.0	12.0	15.6	11.9	14.4	6.39	4.64	<0.54	7.03	13.7	<0.53	21.2
β-HCH	<0.15	<0.17	1.42	1.98	2.60	<0.18	<0.30	<0.20	25.9	11.8	14.3	9.97	11.1
γ-HCH	9.93	4.45	9.30	4.91	7.55	106	4.39	5.31	<0.47	53.3	<0.45	15.2	9.33
dieldrin	31.7	155	555	417	478	332	28.7	13.6	10.1	73.0	50.2	11.2	19.6
Endosulfan I (alpha)	<0.36	<0.31	2.16	<0.46	2.23	3.32	<1.3	2.17	<0.092	<0.36	<0.18	<0.21	<0.22
Endosulfan II (beta)	<1.2	<1.4	<1.2	<1.2	<1.3	<1.3	<2.0	<1.4	<1.2	<1.3	<1.2	40.6	<1.2
Endosulfan sulphate	12.0	14.2	10.1	7.20	9.72	14.2	15.1	12.3	<1.1	<1.2	<1.1	<1.1	<1.1
PBDEs in pg L^{-1}													
BDE47	0.438	1.35	1.15	1.29	2.80	2.28	5.65	0.230	15.0	0.432	0.511	0.570	1.57
BDE66	0.0450	0.0853	0.103	0.118	0.230	0.170	0.496	<0.074	2.38	<0.035	<0.015	<0.019	<0.020
BDE100	<0.037	0.0521	0.0812	<0.050	0.546	0.100	0.446	<0.079	1.87	<0.038	<0.017	0.0755	0.199
BDE99	<0.037	<0.031	<0.025	<0.050	0.659	<0.056	<0.15	<0.079	6.04	<0.038	0.144	<0.020	0.689
BDE153	<0.080	<0.067	<0.054	<0.11	<0.099	<0.12	<0.32	<0.17	0.343	<0.081	<0.035	<0.043	0.119
PCBS in pg L^{-1}													
CB28	7.94	5.70	5.47	6.94	7.65	10.3	23.3	11.9	0.512	31.7	5.45	1.75	4.85
CB52	0.517	3.25	12.7	8.17	8.83	5.95	1.26	2.30	1.87	19.9	12.2	0.64	4.31
CB44	<0.056	0.267	0.726	0.647	0.892	1.02	<0.22	<0.12	0.552	11.7	1.82	<0.031	0.932
CB66	0.660	0.546	1.18	1.22	1.51	1.48	0.979	0.702	0.460	25.6	3.11	0.369	2.22
CB101	3.14	3.07	6.43	6.11	6.64	6.45	7.81	3.83	0.978	4.31	3.06	0.904	2.28
CB118	0.167	0.497	1.59	1.99	2.83	2.13	0.821	0.551	1.03	6.14	2.04	0.764	1.90
CB153	<0.061	2.04	10.1	12.1	9.82	5.24	0.417	0.772	0.48	6.68	4.79	0.585	3.69
CB138	<0.061	1.52	6.92	9.38	8.06	4.68	1.13	1.16	0.88	7.21	3.72	1.03	3.83
CB180	<0.063	0.512	2.19	4.04	2.09	1.08	<0.25	<0.13	0.0460	1.66	0.961	0.111	0.969
PAHs in pg L^{-1}													
Napthalene	3204	446	1016	30.2	476	617	2858	287	568	<4.9	20,456	2605	3786
C1-naphthalenes	3204	987	2092	564	1245	1598	3245	315	313	<1.4	13,325	2817	6082
C2-naphthalenes	389	691	3998	1785	1861	1259	904	182	140	<0.46	1717	583	2401
Acenapthylene	430	688	1330	484	1133	668	471	478	744	345	1113	462	944
C3-naphthalenes	268	931	5031	6293	3027	1777	816	359	486	122	878	664	2478
Acenapthene	8.85	29.1	120	39.9	113	197	23.9	<1.3	45.9	151	88.8	35.8	95.0
Methyldibenzothiophene	8.15	14.1	40.5	77.9	54.8	66.7	2.06	11.4	262	249	115	198	258
Phenanthrene	246	560	834	394	651	638	1222	754	2187	748	1335	1229	1737
Anthracene	0.174	2.17	6.24	2.61	0.737	4.05	<1.0	<0.63	111	6.53	16.2	13.9	43.0
C1-phenanthrenes	59.2	245	863	1132	596	583	503	381	110	35.5	41.9	58.9	119
2-methylanthracene	<0.27	<0.25	20.3	47.1	9.87	5.24	<0.95	<0.52	31.3	36.6	47.7	25.3	62.9
1-methylphenanthrene	18.1	38.7	122	157	105	88.8	95.5	50.7	478	148	476	384	716
C2-phenanthrenes	48.6	165	876	1852	797	595	237	114	343	261	307	271	416
Fluoranthene	94.6	234	367	450	437	715	501	249	64.1	42.7	54.4	52.6	65.0
Pyrene	7.65	28.8	53.4	245	46.5	101	<0.98	<0.54	559	48.7	68.6	78.6	160
1-methylpyrene	<0.28	67.7	139	392	146	159	164	102	1057	142	159	168	245
Benzo[*k*]fluoranthene	1.11	2.67	5.77	14.5	7.07	12.1	<1.0	3.32	28.7	5.55	6.46	2.95	11.2
Benzo[*a*]pyrene	<0.26	<0.22	<0.18	7.07	<0.32	<0.39	<1.0	<0.55	22.8	<0.27	<0.12	<0.14	4.96
Perylene	<0.26	<0.22	<0.18	<0.35	<0.32	<0.39	<1.0	<0.55	93.4	<0.27	<0.12	<0.15	<0.15
Dibenz[*a*,*h*]anthracene	<0.27	<0.23	0.997	1.02	<0.33	0.492	<1.1	<0.57	1.91	1.72	<0.12	<0.15	1.03

Table 2
Functional chemical groupings summary and comparative interpretation data in pg L^{-1} from silicone-sheet passive samplers deployed at various sites in Efate, Vanuatu.

	Vanuatu 2016								Vanuatu 2017				
	Mele Bay	Port Vila Bay					Lagoons		Mele Bay	Port Vila Bay		Lagoons	
All results in pg L^{-1}	Hideaway	Mele Entrance	Cyclone Buoy	Main Wharf	Para Bay	Lycianda wreck	Erakor Central	Emten East	Tiger River Bridge	Fatumaru Bay	Zego pontoon	North Erakor 1	North Erakor 2
SUM DDTs	2.09	5.63	12.4	12.4	22.2	28.9	10.0	7.48	10.0	67.9	24.2	5.96	29.8
p,p′-DDT/p,p′-DDE ratio	N/A	0.541	0.470	0.511	0.553	1.11	0.423	0.605	0.330	0.123	0.334	0.428	0.421
p,p′-TDE/p,p′-DDE ratio	N/A	0.825	1.11	0.694	0.840	1.54	0.492	0.550	0.780	0.214	0.797	0.830	0.528
SUM HCHs	26.1	18.5	22.7	22.5	22.1	120	10.8	9.95	25.9	72.1	28.0	25.2	41.6
γ-HCH/α-HCH ratio	0.613	0.318	0.775	0.315	0.634	7.36	0.687	1.14	N/A	7.58	N/A	N/A	0.440
SUM 25 PCBs	13.6	21.77	67.0	71.4	66.1	52.2	38.8	23.3	10.4	170.0	54.1	7.37	35.3
SUM ICES 7 PCBs	11.8	16.6	45.4	48.7	45.9	35.8	34.7	20.5	5.80	77.6	32.2	5.78	21.8
SUM HBCDs	0.465	2.08	1.06	5.45	1.68	5.24	2.59	4.42	0.753	3.84	1.46	1.48	1.85
SUM PBDEs	0.528	1.68	1.68	1.72	4.86	3.05	7.13	0.346	26.9	0.487	2.72	1.31	4.61
SUM all PAHs and alkyl-PAHs	8112	5443	17,628	14,646	11,326	9731	11,492	3565	8445	2590	40,585	9944	20,441
SUM LMW PAHs	7981	5037	16,840	13,005	10,381	8349	10,632	3122	5845	1986	40,051	9345	19,426
SUM HMW PAHs	492	1393	3374	4891	2893	3047	2840	1691	5556	1577	2606	2345	3801
Anthracene/(phenanthrene+anthracene)	0.0007	0.0039	0.0074	0.0066	0.0011	0.0063	N/A	N/A	0.0483	0.0087	0.0120	0.0112	0.0242
Fluoranthene/(fluoranthene+pyrene)	0.925	0.890	0.873	0.647	0.904	0.876	N/A	N/A	0.103	0.467	0.442	0.401	0.289
Benzo[*a*]anthracene/(benzo[*a*]anthracene + chrysene)	N/A	N/A	N/A	N/A	N/A	N/A	0.748	N/A	0.469	N/A	N/A	N/A	0.329
Indeno[*cd*]perylene/(indeno[*cd*]perylene + benzo[*ghi*]pyrene)	N/A	N/A	0.943	0.939	N/A	0.966	N/A	N/A	0.898	0.807	N/A	N/A	0.940

near the islands of Nguna and Pele also produced a small decrease in growth which cannot be explained in terms of industry or population density.

In Solomon Islands the marine sites sampled by boat did not display any toxicity as determined by the Microtox bioassay, but a few of the land-sampled sites displayed significant reduction in bacteria population growth. In a sample from near the Ranadi landfill site, the measured luminosity was only 35% compared to the control. Samples from near outfalls showed reductions in growth, and there were smaller impacts for several of the rivers and effluent channels that traverse the commercial and industrial areas of Honiara towards the sea (Supplementary Table 4). Of the 47 sites designated as rivers, 17 had results more than 15% below the control growth. These sites were surrounded by macrolitter in the form of plastic waste, cans, glass, and food waste indicating that public litter as well as commercial activity was contributing to the situation.

Although toxicity and measured chemical contamination was generally low, the Solomon Islands passive samplers picked up high combined concentrations for DDT pesticides with total DDTs ranging from 32 pg L^{-1} to 353 pg L^{-1}. This is too low to cause a response in the Microtox assay, but DDT pesticides are likely to bioconcentrate into higher trophic organisms such as game fish and human food resources. Bioaccumulation and then biomagnification through trophic levels can increase body burden up to 10^5 or even 10^6 (HSDB, 1996; Reish et al., 1978). Therefore, whilst water concentrations appear to pose limited acute toxicological impact, future studies should focus on the potential for bioaccumulation through the food chain.

For most sites in Solomon Islands, the sum of low molecular weight (LMW) PAHs was very similar to the sum concentration for high molecular weight (HMW) PAHs. The Central Market sample was much higher for LMW than HMW PAHs, dominated by naphthalene and less so by C1-naphthalenes. These chemicals evaporate rapidly in the environment, so this possibly represents a recent, local contamination event, rather than legacy contamination.

The Vanuatu passive samplers picked up some different contaminants of interest compared to those deployed in the Solomon Islands. Concentrations of dieldrin, another pesticide, were high at many of the sites through Vila Bay in 2016, though notably lower in the Mele Bay and Lagoon samples. This is a chemical which is highly toxic to fish and other aquatic animals. In 2017 the concentrations were generally lower but were again higher in Vila Bay than they were in Tiger River, or Erakor Lagoon. Dieldrin is also a breakdown product of the pesticide aldrin, so the concentrations of dieldrin detected could relate to contamination of sites with either pesticide. The Lycianda Wreck site shows evidence of γ-HCH (lindane) contamination, and the presence of these pesticides and calculated ratios of isomers suggest recent use of DDT, dieldrin and lindane contrary to the prohibition for their use set out in the Stockholm convention (Buccini, 2003). Another pesticide, endosulfan II (beta), was detectable at only one site, North Erakor, on one occasion. This single appearance possibly suggests very localised and restricted duration usage. Passive samplers are particularly useful in detecting irregular chemical release and can provide evidence of poorly regulated practices that spot sampling might miss.

High naphthalene concentrations were detected near a pontoon in Vila Bay, which is attributed to the high frequency of motorboats used within that area of the Bay, indicating that such activity has the potential to act as a point source for hydrocarbon contamination of the local area.

These results represent samples of water-based contamination at two large urban and commercial centres in the islands of the South Pacific. The passive samplers are a useful alternative to traditional spot sampling (Miège et al., 2015; Booij et al., 2016) and have indicated low concentrations for most chemicals tested but have also indicated that further investigation may be required to understand the situation with pesticides and naphthalenes. A large sum PAH value for the Solomon Island samplers, despite low individual values, might steer concerns towards possible chronic impacts caused by multiple sources. Chronic effects are

Table 3
Chemical analysis data in pg L^{-1} from silicone-sheet passive samplers deployed at various sites in Guadalcanal, Solomon Islands.

	Solomon Islands 2017		Solomon Islands 2018/19			
	Domestic Wharf	Central Market	Boneghe	Point Cruz West	Point Cruz East	Mataniko
Pesticides in pg L^{-1}						
HCBD	<0.016	<0.038	0.116	0.0495	0.135	0.132
HCB	2.55	2.37	2.15	1.79	1.59	1.78
α-HCH	10.8	9.77	10.0	9.10	7.14	8.41
β-HCH	37.4	8.59	7.40	15.8	8.96	9.84
γ-HCH	25.7	18.0	20.7	19.5	21.0	19.8
Dieldrin	31.0	17.0	2.98	15.6	30.0	14.4
Endosulfan I (alpha)	<0.095	<0.23	<0.28	<0.26	<0.23	<0.23
Endosulfan II (beta)	<1.2	<1.8	<1.2	<1.3	<1.2	<1.1
Endosulfan sulphate	<1.1	<1.7	<1.1	<1.2	<1.1	<1.1
PBDEs in pg L^{-1}						
BDE47	1.13	3.31	<0.027	2.86	0.433	2.05
BDE66	0.0939	<0.019	<0.027	<0.023	<0.021	<0.021
BDE100	0.246	0.374	<0.029	0.451	<0.023	0.376
BDE99	1.09	1.23	<0.029	1.74	0.311	1.19
BDE153	0.0689	0.221	<0.061	<0.053	<0.048	<0.048
PCBs in pg L^{-1}						
CB28	1.94	2.81	2.55	2.38	2.57	2.14
CB52	2.36	1.09	0.527	0.776	1.50	1.22
CB44	0.811	0.734	<0.043	0.247	0.720	0.729
CB66	1.17	1.14	0.600	0.673	1.15	1.07
CB101	1.34	0.988	0.722	1.07	1.08	0.702
CB118	1.24	0.891	0.223	0.918	1.13	0.847
CB153	1.54	0.783	<0.047	0.785	0.825	0.619
CB138	1.81	1.26	0.266	1.54	1.96	1.12
CB180	0.421	0.266	<0.049	0.315	0.421	0.224
PAHs in pg L^{-1}						
Napthalene	9849	12,123	<4.8	<5.0	<4.6	<4.6
C1-naphthalenes	4923	4046	<1.4	<1.4	<1.3	<1.3
C2-naphthalenes	1761	205	<0.42	<0.42	<0.39	<0.38
Acenapthylene	<2.8	215	<2.8	<2.9	<2.7	<2.7
C3-naphthalenes	5781	1510	<0.22	1238	976	763
Acenapthene	176	4.99	81.0	<1.3	<1.2	3.37
Methyldibenzothiophene	96.5	96.9	68.0	88.1	23.9	26.6
Phenanthrene	7459	1855	222	1200	860	710
Anthracene	686	44.9	<0.37	28.7	35.1	17.4
C1-phenanthrenes	284	103	15.0	82.0	62.4	49.5
2-methylanthracene	2524	146	19.0	176	191	141
1-methylphenanthrene	8960	890	224	703	736	517
C2-phenanthrenes	206	167	47.0	109	129	127
Fluoranthene	5002	181	32.0	117	195	151
Pyrene	1359	58.2	13.8	60.1	149	127
1-methylpyrene	4348	174	6.94	80.0	278	194
Benzo[*k*]fluoranthene	27.9	6.09	<0.20	5.30	11.6	10.7
Benzo[*a*]pyrene	13.2	2.45	<0.20	<0.18	9.73	6.42
Perylene	5.91	2.20	<0.20	<0.18	31.5	37.4
Dibenz[*a,h*]anthracene	5.67	<0.15	2.56	0.803	1.35	<0.16

more complicated to detect compared to acute toxicity caused by higher concentrations or more toxic chemicals.

The Microtox test has been shown to be a useful screening tool (Colvin et al., 2020), providing an indication of the overall impact of the combined chemical load. It can be used as a tool to identify areas of localised toxicity and to target remediation efforts at the areas which are exhibiting the biggest impacts. In the absence of broader testing, this can cautiously be used to indicate the potential for toxicity on higher organisms (Parvez et al., 2006), although a battery of tests would be recommended to generate deeper understanding (*e.g.* Thain et al., 2008; Lyons et al., 2010; Wernersson et al., 2015; Vethaak et al., 2017;). Data in this study showed that rivers and effluents were more likely to be toxic than nearshore and coastal sites, which reflects the accepted wider body of environmental ecotoxicology data, and suggests the technique might be an effective screening tool in the absence of ecotoxicology laboratories. In Vanuatu, specific river sites and effluents were shown to have concerning toxic impacts. Solomon Island samples indicated that many rivers might be carrying sufficient noxious chemicals to negatively impact the test, and the small river near the Ranadi landfill site was the most impacted site we measured in Guadalcanal.

The data presented here and in the extended supplementary data generates some much-needed baseline data on the concentration and impacts of a range of organic chemical contaminants. Such data is sparse or completely missing across the region (Varea et al., 2020) and as such these studies contribute useful information to national and regional data sets. The data could also contribute to the national reporting and surveillance commitment required by signatories of the Stockholm convention, as well as local assessment of the impacts and potential legacy issues related to the use and disposal of POPs and other environmental contaminants of concern.

This research utilised techniques that can be deployed easily in the field in areas where temperature, transport and infrastructure make it difficult to carry out large scale multi-parameter monitoring and sample analysis. The samples represent contaminants in the water column at the point of sampling, so they are likely to be a measure of current rather than legacy contamination.

Table 4
Functional chemical groupings summary and comparative interpretation data in pg L^{-1} from silicone-sheet passive samplers deployed at various sites in Guadalcanal, Solomon Islands.

	Solomon Islands 2017		Solomon Islands 2018/19			
All results in pg L^{-1}	Domestic Wharf	Central Market	Boneghe	Point Cruz West	Point Cruz East	Mataniko
SUM DDTs	159	221	32.4	253	353	295
p,p′-DDT/p,p′-DDE ratio	0.662	0.853	0.63	0.344	0.363	0.368
p,p′-TDE/p,p′-DDE ratio	2.44	1.63	0.711	0.379	1.04	1.11
SUM HCHs	73.9	36.4	38.1	44.4	37.1	38.1
γ-HCH/α-HCH ratio	2.38	1.84	2.07	2.14	2.94	2.35
SUM 25 PCBs	20.8	15.5	5.74	12.1	18.5	14.1
SUM ICES 7 PCBs	10.7	8.09	4.29	7.78	9.49	6.87
SUM HBCDs	4.27	0.544	0	0.193	0.502	0.366
SUM PBDEs	4.08	5.5	0	5.3	0.744	3.83
SUM all PAHs and alky lPAHs	55,021	22,153	808	4164	3917	3053
SUM LMW PAHs	43,229	21,485	608	3600	2990	2328
SUM HMW PAHs	31,397	3711	614	2644	2809	2178
Anthracene/(phenanthrene+anthracene)	0.0842	0.0236	N/A	0.0234	0.0392	0.0239
Fluoranthene/(fluoranthene+pyrene)	0.786	0.757	0.699	0.661	0.567	0.543
Benzo[*a*]anthracene/(benzo[*a*]anthracene + chrysene)	0.541	N/A	N/A	0.106	N/A	N/A
Indeno[*cd*]perylene/(indeno[*cd*]perylene + benzo[*ghi*]pyrene)	0.885	N/A	0.645	0.889	0.866	N/A

Table 5
Microtox results for sites assessed in Efate, Vanuatu during 2016 and 2017. 68 samples total, divided into locations or functional site types. Numbers represent the % luminescence produced by a population of bacteria, compared to the luminescence increase in a control, which is scored as 100%. The most toxic sample, from the market sewer with a toxicity of 50%, has been removed from the Port Vila data set as a clear outlier.

	Port Vila	Lagoons	Mele Bay	Efate Coastal	Rivers
Mean	102.0	105.0	94.4	105.6	92.6
Max	122	117	102	124	123
Min	84	97	91	87	63
St Dev	7.9	8.3	3.6	12.1	20.3
Count	35	5	9	9	9

Table 6
Microtox results for sites assessed in Guadalcanal, Solomon Islands during 2018 and 2019. 101 samples total divided into locations or functional site types. Numbers represent the % luminescence produced by a population of bacteria, compared to the luminescence increase in a control, which is scored as 100%. Sites classed as Effluents varied greatly in size, flow, and toxicity.

	West of Rove	Honiara Central	East of Ranadi	Rivers	Effluents
Mean	119.9	129.3	127.7	95.0	93.9
Max	136	150	146	120	125
Min	102	106	106	64	35
St Dev	9.0	12.6	11.7	15.9	27.0
Count	10	28	7	47	9

CRediT authorship contribution statement

A.J. Smith: Conceptualization, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **J. Barber:** Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **S. Davis:** Investigation, Formal analysis, Writing – review & editing. **C. Jones:** Formal analysis, Visualization. **K.K. Kotra:** Resources, Writing – review & editing. **S. Losada:** Formal analysis, Writing – review & editing. **B.P. Lyons:** Investigation, Supervision, Funding acquisition, Writing – review & editing. **M. Mataki:** Resources, Writing – review & editing. **K.D. Potter:** Formal analysis, Writing – review & editing. **M.J. Devlin:** Investigation, Supervision, Funding acquisition, Writing – review & editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

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