Transforming place-based management within watersheds in Fiji: the Watershed Interventions for Systems Health project

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Abstract

Watersheds offer opportunities for place-based interventions to transform systems health via preventative versus reactive approaches to management that achieve multiple co-benefits for public and environmental health. The Watershed Interventions for Systems Health in Fiji (WISH Fiji) project embraced participatory knowledge co-production and action-oriented research to identify risks to public and ecosystem health, prioritize interventions to address risks, and monitor responses of the system to interventions. We used screening filters and local knowledge to collaboratively identify five watersheds for action with high prior incidence of water-related diseases (Fiji's "three plagues" of leptospirosis, typhoid and dengue) and high risk to downstream environmental health. We reviewed literature to identify disease risk factors, evaluated overlaps with risks for downstream environmental impact, and designed 13 instruments to collect information about baseline risk. Following consultations to obtain free, prior and informed consent, we enrolled 311 households across 29 communities. We synthesized data to identify key risks at the household, community, and landscape level, which were communicated to community water and resource management committees and government leaders as part of developing water and sanitation safety plans for each community. Local committees identified 339 priority risk reduction actions across nine main categories: animal management; drainage; health systems surveillance; hygiene; integrated planning; land use management; sanitation systems; waste management; and water systems. As of October 2022, 154 interventions were implemented in the five watersheds across different risk categories and scales. While we can track changes to factors that reduce risk of water-related disease and improve environmental health, direct evaluation of impacts to public health is limited due to poor geolocation of case records. The WISH Fiji project is a model of cross-sectoral coordination that efficiently progresses multiple Sustainable Development Goals, but scaling requires sustained investment in interventions to realize full benefits, particularly for nature-based solutions that exhibit lagged responses.

1. Introduction

There is broad recognition that bounded, watershed systems are ideal for integrated management of water resources for environmental and social outcomes [1]. There has been less attention to the opportunities and complexities of managing systems health through a place-based lens focused on watershed management and governance [2-4]. Systems health is the emergent result of functioning interdependencies, interactions and feedbacks between ecological and sociocultural settings across nested scales [5, 6]. Downstream environmental impacts from upstream human modification of watersheds are well-documented across geographies and latitudes [7-9], but there is limited understanding about how those impacts relate to changes in social systems, particularly domains of human health and well-being, and how these are modulated by environmental change.

Emerging evidence provides a new appreciation for ways in which human activities within watersheds directly and indirectly contribute to the spread of water-related disease [10-12]. Globally, diarrheal diseases are the third leading cause for morbidity and mortality in children less than 10 years, accounting for a greater disease burden than AIDS, malaria, and measles combined [13]. In 2016, unsafe drinking water contributed to 484,741 deaths (36% of diarrheal deaths) for all ages in low and middle income countries [14]. The estimated global burden of all inadequate water, sanitation and hygiene (WASH)-related diseases (including diarrhea) amounts to 1.6 million deaths (2.8% of all deaths; [14]). Women and girls are disproportionately impacted by these diseases given gendered aspects of water collection, food preparation and sanitation [15]. While there is evidence that outbreaks of water-related diseases (both water-borne and vector-borne) are amplified by environmental factors related to climate change, land use, and changing social conditions [16, 17], it is difficult to associate specific watershed activities with disease incidence because health systems surveillance data are typically collected across jurisdictional units that do not match watershed boundaries [18, 19].

Pacific Island countries and territories (PICTs) are particularly vulnerable to water-related disease. As such, the World Health Organization (WHO) considers the cross-sectoral control of water-related disease among the highest priority health security issues for the Western Pacific Region [20]. The region has the lowest access to safe drinking water sources, with 41% of the population relying on surface water and other unimproved sources [21]. Access to an improved drinking water source is higher in Fiji, with 94% of the population accessing a basic service, however, there is no published data on whether those sources are safely managed [21]. The most recent Fiji Government estimates are that 37% of Fiji's wastewater is disposed directly into land and marine environments [22] and there is no available national data on the portion of sanitation systems that are safely managed [21]. Fiji has had over 20 reported typhoid outbreaks since 2005 [23], a 27,000 case outbreak of dengue in 2013-2014 [18], and multiple outbreaks of leptospirosis post-cyclone and heavy rainfall events [24].

Fiji presents a model geography for approaching systems health within watersheds given the large body of work documenting negative impacts to freshwater and marine ecosystems and species linked to loss of forest cover (particularly around riparian zones), alteration to hydrological regimes, and upstream agricultural activity within watersheds [25-28]. These studies are complemented by empirical data and models from other Pacific, tropical high islands documenting links between land use (e.g., forestry, livestock) and water quality and safety [29, 30]. Some of these same drivers of environmental change are also known correlates or predictors of leptospirosis [31] and typhoid [11], two of Fiji's "three plagues" (also including dengue, and collectively referred to as "LTD"). Jenkins and Jupiter [24] present a conceptual model of systems health within Fiji watersheds under which the combination of watershed modification and heavy rainfall events produce multiple, interacting pathways leading to ill-health through: damage to water and sanitation infrastructure, allowing pathogens to enter food and water sources; crowding of animals and people, which increases risks of zoonotic disease transmission; and increased floodwaters, that create habitat for mosquito vectors and also contain associated runoff of sediments and nutrients, which may serve as sites of carriage for bacterial pathogens.

In this paper, we present a case study from the Watershed Interventions for Systems Health in Fiji (WISH Fiji) project that was designed specifically to address multiple drivers of ill-health to people and the environment that operate and interact at nested scales and through multiple pathways within watersheds [6]. WISH Fiji was designed on the premise that ecosystems, particularly in rural settings, form the foundations for achievement of Sustainable Development Goals (SDGs) related to zero hunger, good health and well-being, and clean water and sanitation, among others [32, 33]. We used participatory, research-action approaches that engaged best practice for knowledge co-production across stakeholder groups, sectors and disciplines [34, 35], and we inserted broader systems thinking into traditional tools for water safety planning. We also consciously built on Pacific Islander connections to place, rooted in customary tenure systems, which offer unique opportunities for action because of recognized landowner rights to determine how land resources are used and managed [36, 37].

Below we describe the innovations undertaken within WISH Fiji to: work collaboratively with key stakeholders to select project sites based on risk criteria; implement extensive free, prior and informed consent (FPIC) consultations; identify potential systems health risks based on literature review; design instruments to measure baselines within five watersheds; set risk level thresholds for each factor; and co-design and implement watershed interventions based on identified risks and participatory water and sanitation safety planning. We discuss outcomes from our flexible, adaptive approach that are realized, anticipated and also challenging to measure due to limitations in health systems data collection. Lastly, we provide key lessons for implementing research-action approaches to building systems health in other contexts and recommendations for sustaining long-term practice.

2. Methods

2.1 Fiji geographic overview

Fiji is an archipelagic nation in the southwest Pacific with over 330 islands and 550 smaller islets, covering a land area of 18,270 km^2. Larger watersheds are located on the major high islands of Viti Levu, Vanua Levu, Taveuni, Kadavu, and Ovalau. Mean annual rainfall ranges between <2,000 mm on the northwestern sides of the larger islands in the shadow of prevailing southeasterly trade winds and >3,200 mm on the southeastern sides [11]. As with most other Pacific Islands, the original Indigenous settlers significantly changed the natural vegetation structure, with forests replaced by herbaceous communities [38]. Following arrival of European colonizers in the 1800s, further large-scale landscape changes within watersheds resulted from commercial logging and agriculture (e.g., sugarcane), livestock, and urban and coastal development. As of the 2017 census, Fiji had a population of 884,887, of which 44.1% reside in rural areas [39]. In 2007, the most recent records of population breakdown by ethnicity, 56.8% of the population identified as Indigenous (*iTaukei*), while 37.4% identified as Indo-Fijian (of Indian descent) and 5.8% as other [40]. *iTaukei* Fijians have tenure, and thus decision-making rights, over 88% of Fiji's land, held at the *mataqali* (similar to clan) level [41]. The largest administrative units in geographical size are divisions (Central, Western, Northern, and Eastern), followed by provinces (14 in total), *tikina* (86 in total), and enumeration areas (the smallest unit for population census that typically include 80 to 120 households).

2.2 Watershed Management in Fiji

There is no formal plan or policy that provides an overarching framework for watershed management, though the Integrated Coastal Management (ICM) Framework 2011 lays out a process that Fiji could follow to develop a national coastal plan, inclusive of coordinating and regulating activities in upstream watersheds [42]. At present, despite the Department of Waterways' strategic objective for "sustainable management of waterways and watersheds" [43], policies regulating upstream activities are piecemeal and poorly coordinated across agencies that sometimes have overlapping jurisdictions, which confounds responsibilities for enforcement [44]. Individual communities or collectives of communities have drafted ecosystem-based management (EBM) plans that include rules governing use and access of ecosystems and resources to which they commit themselves to follow on a voluntary basis [45], and some ICM plans have been developed at the provincial level [46]. In October 2022, Fiji's Cabinet endorsed a new National Drinking Water Quality Committee, with a mandate to provide evidence of safe drinking water, even in rural areas, "through sanitary surveys, water safety plans, and drinking water quality monitoring and surveillance programs and integrating it with water-related disease surveillance" [46], which may help facilitate improved coordination for water management and governance.

2.3 The WISH Fiji project

The WISH Fiji project involves a research consortium between two Australian universities, a Fijian university, the Fiji Ministry of Health and Medical Services (MoHMS), WHO, the United Nations Children's Fund (UNICEF), the Pacific Community (SPC) and the Wildlife Conservation Society (WCS), established with funding from the Australian Government's Indo-Pacific Centre for Health Security and Bloomberg Philanthropies' Vibrant Oceans Initiative [6, 33]. WISH Fiji has five goals, to: reduce the incidence of water-related diseases in people and downstream ecosystems; empower communities to access and maintain their fundamental right to clean water; strengthen connections to place to enhance environmental stewardship and maintain cultural practice; develop a coordinated mechanism for systems health governance; and facilitate approaches to sustainable finance and scale interventions. The project was designed to use knowledge co-production approaches in order to encourage uptake and ownership of watershed management and governance by landowners and government. WISH Fiji has been undertaken through a series of steps to identify, communicate and reduce risk through an adaptive management approach (Fig 1). Each of the steps are described in brief below.

Fig 1. Project risk reduction methodology steps within an adaptive management cycle. (a) Workshop with government representatives to select project watersheds. Photo © Aaron Jenkins. (b) Water quality sampling during baseline data collection. Photo © Tom Vierus. (c) Awareness materials designed to communicate risk factor concepts. © cChange. (d) Community water and sanitation safety planning meeting. Photo © Kelera Naivalu. (e) Installation of water tank and pipes. Photo © ZoomFiji.

2.4 Ethics

WISH Fiji received ethics approval from the Fiji National Health Research and Ethics Review Committee (FNHRERC No: 2018.231.CEN), Fiji National University's College Health Research Ethics Committee (CHRED ID: 009.19), the University of Sydney's Human Research Ethics Committee (2019/588) and Edith Cowan University's Human Research Ethics Committee (#2019-00618).

2.5 Watershed selection process (Step 1)

To facilitate the project site selection, the WISH Fiji team: devised a list of selection criteria for project watersheds; held a national-level workshop with key stakeholders from government and civil society to apply the criteria; and then presented the proposed watersheds to the interim National Drinking Water Quality Committee chaired by MoHMS for consideration and final decision. To be suitable for selection, a watershed needed to have all the following primary characteristics: sufficient records to demonstrate recent outbreaks of at least two of the three LTDs in the prior two years; at least six identifiable communities within its boundaries; and known concerns about drinking water quality, health-related climate vulnerability, impacts of recent natural disasters and/or poor water and sanitation infrastructure. To ensure consideration of the whole linked watershed-to-reef system, we also required at least two of the watersheds to be coastal and to discharge to the ocean. Upon satisfying these primary criteria, short-listed watersheds were evaluated according to the following secondary criteria: accessibility; characterization as primarily rural; not concurrently receiving other significant assistance/funded support in WASH, environmental management, or other areas that would compromise the ability of the project to detect changes in risk factors; and potential for leveraging resources from other agencies to support implementation of prioritized interventions. These processes resulted in the selection of five project watersheds (Fig 2), for which the major defining features are described in Table 1.

Fig 2. Locations of WISH Fiji project watersheds in Fiji: (a) Dawasamu and Waibula; (b) Upper Navua; (c) Bureta; and (d) Dama. Black circles indicate project villages.

Table 1. Major demographic, geographic, development and management characteristics of five project watersheds. EBM: ecosystem-based management; WASH: water, sanitation and hygiene.

	Bureta	**Dama**	**Dawasamu**	**Waibula**	**Upper Navua**
Province	Lomaiviti	Bua	Tailevu	Tailevu	Namosi
Division	Eastern	Northern	Central	Central	Central
Population	1,089	2,826	1,614	6,119	1,558
Area (ha)	3,155	9,610	7,450	26,692	13,896
Main river length (km)	10	20	8	32	28
Dense forest cover (%)	97	82	79	84	93
Major development activities	Commercial agriculture (i.e., kava) Small-scale agriculture	Plantation forest Small-scale agriculture	Gravel quarry Small-scale agriculture	Commercial dairy farming Small-scale agriculture	Small-scale agriculture
Natural Resource Management	Ovalau Island EBM Plan Ovalau Forest Conservation Area	Dama District EBM Plan	Coastal management & WASH activities supported by Global Vision International	Nursery for restoration established at 1 project village	Namosi Provincial Resource Management Plan 2017-2019

Across all five watersheds there is a total population of 13,206, ranging from the lowest population in the smallest watershed (Bureta, 1,089 people) to the greatest population in the largest watershed (Waibula, 6,119 people). The headwaters of all watersheds are well-forested. Waibula and Dawasamu are low gradient, coastal watersheds with alluvial and depositional hydrology in the lower reaches. The Upper Navua River forms the headwater section of the larger Navua River watershed and is steep and mountainous, with erosional, colluvial and depositional features. In

Dama and Bureta watersheds, rivers flow through moderately steep, coastal watersheds with erosional and colluvial features.

2.6 Community selection and free, prior and informed consent (Step 2)

Project communities were selected through consultations with provincial government staff who had knowledge of presence of prior outbreaks of LTDs and local knowledge of where there was likely to be disease risk that could be addressed through project interventions. Across the 29 communities selected, most of the population is of *iTaukei* origin, though two communities have a majority Indo-Fijian population. Our free, prior and informed consent (FPIC) process began with a series of consultations with the Ministry of iTaukei Affairs (MiTA), responsible for developing, implementing, and monitoring government programs focused on the governance and well-being of *iTaukei* people. In the absence of a formal government process for community-level FPIC, we co-designed a process with MiTA tailored to the Fijian context based on international best practice guidelines [47]. Prior to approaching the 29 communities, detailed discussions on WISH Fiji planned activities were held with key government ministries influential in the watersheds, including MoHMS, Agriculture, Forestry, Lands and Mineral Resources, and MiTA. Over a five-month period, we conducted a three-phased FPIC process in all 29 communities which focused on: initial visits to local and provincial government partners to describe project objectives; comprehensive community awareness sessions with participation of broad segments of each community, including men, women, elders and youth; and, following adequate time for internal community discussion, a final visit to each community with representatives from MiTA to obtain granted signed consent. When all phases of FPIC were completed for all communities, we then undertook household-level consent for the 311 households enrolled in the project (see *Step 4* below).

2.7 Survey instrument design (Step 3)

Our next step was to understand to what extent: individuals in a community were at risk of being exposed to an LTD infection or a diarrheal disease; and downstream ecosystems were at risk from upstream land-based activity. A search of the literature revealed specific risk factors which could be assigned within nested spatial scales, from watershed (consisting of largely environmental and landscape factors), to community, to the household and individual-level. Watershed risk factors were defined by environmental and landscape parameters, evaluated at the 'sub-catchment' level, which we define here as inclusive of all upstream areas that drain to primary water sources identified during community mapping (see S1 Table). Community-level risk factors were inclusive of infrastructure and services, as well as proximity of swamp and proximity of livestock to water sources, which affected each community. Various demographic, socio-economic, and behavioural factors, as well as some household-level infrastructure, were relevant at the household and individual-levels. We selected risk factors that were applicable to one or more individual diseases or downstream ecosystem impacts. Our literature review was also used to identify survey instruments that could be used to gauge the degree to which communities were vulnerable to these risk factors. Accordingly, we identified and adapted existing and developed new instruments that could be applied at an appropriate level. Relevant instruments are shown in Table 2, which represents a subset of the full set of instruments applied over the duration of WISH Fiji (see [48, 49] for additional instruments).

Table 2. Types of data collection instruments designed by the WISH Fiji team to measure risk factors at watershed/sub-catchment, community and household/individual scales. References are indicated when the instruments were adapted from prior sources.

Instrument	Risk factor coverage	Source
A. Government Scoping	Details of government activities in watershed areas that may influence water quality	Direct development by team
B. Community Mapping	Details of community water infrastructure, events, threats, hazards, and other activities that may influence water supply and quality	Direct development by team
C. Agriculture	Agricultural activities, livestock management and land use in sub-catchment	Adapted from WHO [50]
D. Fisheries & Aquaculture	Fisheries and aquaculture practices that may influence water quality	Adapted from WHO [50]
E. Sanitation Mapping	Details on and observations of sanitary facilities in communities	Adapted from WHO [50]
F. Recreation	Recreational activities and sites in sub-catchment that may influence exposure to contaminated water or mosquito vectors	Adapted from WHO [50]
G. Household Observation	Observation of household environment, hygiene and sanitary facilities, including drainage and potential hazards	Adapted from WHO [50]
H. Household Sanitation Survey	Details of household health sanitation infrastructure and maintenance	Direct development by team
I. Household Questionnaire	Details of household health behaviours and practices	Adapted from WHO [50]
J. Environmental Sampling	A method for sampling of water and soil for physical, chemical, microbiological analyses, which included datasheets for field and laboratory tests	Direct development by team
K. Community Health Care Worker Questionnaire	Details of disease events in communities	Direct development by team
L. Village Head or Delegate Questionnaire	Details of livestock and agricultural practices provided by key informants as a supplement to instrument C	Direct development by team
M. Water and Sanitation Safety Plan Process and Cyclic Review	Details of community water and sanitation systems to complement instruments E, H, I, as well as to identify threats to water supply and quality, to complement instrument B	Adapted from UNICEF [51] and WHO [52]

2.8 General methodology for data collection (Step 4)

Instruments were applied during a baseline data collection phase between August and December 2019. Within the 29 communities, 311 (21%) out of 1,502 households were selected for survey and observation. To select households, each was assigned a unique number, all numbers were placed in a bowl and were selected one by one until at least 15% of households per community were selected (or a minimum of 6 households for communities with less than 40 households; [48]). Data collection was supervised by a nominated coordinator for each watershed ("Catchment Coordinator") with a team of trained project staff and volunteers during an intensive phase of interviews, surveys and observations, over a period of about one week per community. A water quality monitoring program was designed and simultaneously implemented to assess risk at three scales: (1) watershed-level: river and creek water (from ridge to reef); (2) community-level drinking water sources and piped distribution networks; and (3) household-level drinking water (piped and stored). This longitudinal approach produced a dataset that could be used to observe changes in the watersheds and communities. Water was sampled in sterile 500 mL bottles and all analysis was conducted using portable field kits (Wagtech, Palin, UK). Faecal indicator bacteria were measured in the field using membrane filtration with m-ColiBlue24 reagent (method 10029 Hach, USA) which gives counts of *Escherichia coli* (*E. coli* cfu/100 mL). All survey data were used to evaluate pre-intervention systems health state (see *Step 5*), as well as to highlight risk factors requiring attention (*see Step 6*).

2.9 Identifying risks across nested spatial scales (Step 5)

Implementation of the instruments described for *Steps 3* and *4* generated a significant amount of data from each community. The first phase of data analysis focused on 22 known risk factors by: removing variables that were not reliably measured; removing variables that were not able to discriminate between communities or between households; removing highly correlated variables that repeatedly showed the same response; and combining variables into a composite indices to represent a more comprehensive risk factor (e.g., for "livestock near water", see S1 Table). In addition, certain factors (i.e., socio-economic and demographic variables), which have been documented to have associations with disease risk, are not considered here because we could not intervene to change them. Supplementary S1 Table provides a detailed explanation of the 22 risk factors, arranged according to: sub-catchment factors determined from geospatial and water quality data; community factors measured through observations or water quality data collected by field teams using instruments (instruments B-F and J-L; Table 2); and household/individual factors measured from survey instruments (instruments G,H,I; Table 2) and household water quality sampling (instrument J; Table 2). The source data and measurement methods are described for each risk factor, along with threshold values used to categorize low, medium and high risk, where the thresholds between low, medium and high risk represent testable assumptions drawn from the literature, field observations, or discussions in each community arising from the water and sanitation safety planning process (see *Step 7*).

2.10 Communication tool design (Step 6)

We contracted cChange, a nonprofit organization specializing in designing communications products for nature-positive behavioural change, to develop flip charts with graphics that illustrate how activities at the watershed, community and household/individual level create risks for LTDs and ill-health in downstream ecosystems. Each graphic illustrating risk was paired with a solution-space graphic that indicated recommended interventions to reduce risk: versions were produced with accompanying text in both English and *iTaukei*. Our project team developed a script to guide facilitators in explaining the graphics during meetings with each community. Flip chart discussions were paired with Powerpoint presentations of the baseline data results in each community, highlighting where medium and high-risk factors were observed. These presentations were made in concert with meetings to undertake water and sanitation safety planning (see *Step 7*).

2.11 Water and sanitation safety planning (Step 7)

Our water and sanitation safety plan (WSSP) process engaged communities to identify and address risks related to drinking water, solid waste, sanitation and hydrological systems using a combination of UNICEF's Drinking Water Safety and Security Planning (DWSSP) implementation cycle [51] and WHO's Sanitation Safety Planning process [52] tailored to the Fiji context and with added attentiveness to activities occurring in the sub-catchment area around drinking water sources. The six iterative components of this community-level, adaptive management process were: *preparation*, by collating community details, assembling the team and assessing any existing water or sanitation plans; *documentation*, by describing in detail community and household-level drinking water supply and sanitation systems; *hazard mapping*, by identifying and assessing hazards and exposure risks (within 0.5 km of drinking water sources), hazardous events, and existing control measures; *planning*, led by community members to identify priority actions to minimize risks; *implementation*, through community stewardship of each WSSP through coordination of intervention implementation and infrastructure maintenance; and *cyclic review*, to improve and document all aspects of WSSP implementation. The initial WSSP process started in mid-August 2020 and was completed by mid-October 2020. Because several communities were severely damaged by tropical cyclones Yasa and Ana in December 2020 and January 2021, respectively, these communities' WSSPs were updated in early 2021 to reassess their post-cyclone WASH needs.

2.12 Intervention prioritization process (Step 8)

Decisions about resourcing watershed interventions by the project team were influenced by: cost, including balancing investment as equitably as possible across project watersheds; urgency, given impacts to water infrastructure by tropical cyclones Yasa and Ana and COVID-19 transmission mitigation; feasibility, given travel restrictions and supply chain issues associated with COVID-19; ability to obtain landowner permissions; and knowledge of partner resources that could be leveraged to support other interventions. These decisions were made considering the complexity and financial viability of each proposed intervention in the context of community capacity. We categorized proposed interventions into five types of work: (A) watershed or sub-catchment scale (e.g., long-term reforestation activities across large scales), requiring major resources (> US$500), complex procurement to outsource external skills, and coordination of multiple stakeholders; (B) community-level (e.g., infrastructure construction by tradesmen), requiring major resources (> US$500) and complex procurement to outsource external skills; (C) community-level (e.g., simple infrastructure construction), requiring major resources (>US$500) but where there was local capacity to complete the work; (D) community-level (e.g., small repairs, simple construction), requiring minor resources (<US$500) and where there was local capacity to complete the work; and (E) community-level (e.g., policy enforcement, community decisions or basic repairs), where no physical resources were needed and the community has the capacity to do the work. Costs were estimated through quotes obtained from vendors and service providers. Determination of the complexity of work and local capacity available was done with local WISH Fiji project managers and Catchment Coordinators.

3. Results

There was considerable variability in observed and measured risk across risk factor, watershed, and community (detailed in S2 Table), with some specific patterns emerging. By far, the most ubiquitously high risks were associated with the poor coverage of safely managed sanitation in the community and high numbers of enrolled households had damaged or overflowing sanitation infrastructure (Table 3, S2 Table). A suite of factors had either medium or high-risk for more than

70% of communities. These included: the average *E. coli* calculated for environmental water samples, from each community; the presence of swamps proximal to the community; issues associated with livestock near water; perceived adequacy of drinking water supply; and frequent reports of householders working in wet environments (Table 3).

Table 3. Number of communities categorized in low, medium and high risk categories for each of the risk factors, from 2019 baseline data. HEA(%): The amount of highly erodible soil area in the sub-catchment; HFRA(%): amount of high flood risk area in the sub-catchment; CC/km: number of creek crossings per km of road; FF/km: forest fragments in the riparian buffer zone per km of river. Data are derived from supplementary S2 Table.

Risk	**Low**	**Medium**	**High**
Sub-catchment			
River water *E. coli*	6	9	12
HEA(%)	10	8	11
HFRA(%)	14	6	9
CC/km	9	18	1
FF/km	23	5	1
Community			
Flooding	23	5	1
Swamps	8	9	12
Livestock near water	5	14	4
Sanitation safety	0	6	23
Sanitation infrastructure damage	8	6	15
Primary drinking water *E. coli*	10	11	7
Household/residential			
Drinking water supply adequacy	6	19	4
Piped drinking water *E. coli*	12	9	8
Stored drinking water *E. coli*	6	8	6
Wash hands (food)	17	10	2
Wash fruit/vegetables	27	2	0
Working environments	3	22	4
Using river	15	11	3
Pools	11	16	2
Bushes	11	16	2
Water Containers	15	7	7
Ditches	12	10	5

Some risk factors revealed remarkably similar patterns across the communities. For example, there was the same distribution of communities spread across risk categories for factors related to standing water around the house and cutting of bushes in the yard. In other cases, patterns varied.

While most communities were low risk for hygiene factors related to the frequency of washing fruit and vegetables and frequency that the food preparer washes hands before cooking, 41% of communities had medium to high risk associated with hand washing (Table 3).

At the watershed level, patterns also emerged (Table 4). In addition to the risk factors that were elevated across a majority of communities described above, Waibula and Bureta communities showed elevated risk due to large quantities of high flood risk area within sub-catchment boundaries. Dawasamu, Waibula and Namosi communities had elevated risk from large areas of highly erodible soil within sub-catchment boundaries. Dawasamu and Waibula communities had elevated risk from the presence of various types of mosquito breeding habitat. Further, compared to the other watersheds, Namosi and Bureta communities had elevated risk due to higher levels of *E. coli* detected in river water, primary drinking water sources, and piped and/or stored water. Individual communities within each watershed also showed elevated risk for specific factors, such as standing water around households, low frequency of cutting bushes near households and working in wet environments (S2 Table). These community-level risks provided specific guidance for WSSP processes and required interventions.

Table 4. Patterns of elevated risk across the five project watersheds. Here 'x' represents instances where risk factors or groups of risk factors were high and/or medium across all communities in a project watershed at baseline.

Risk type	**Dawasamu**	**Waibula**	**Namosi**	**Dama**	**Bureta**
River water quality issues			x		x
Highly erodible soils	x	x	x		
High amounts of high flood risk area		x			x
Proximity of swamps	x	x	x	x	
Livestock near water				x	
Sanitation issues	x	x	x	x	x
Drinking water quality issues			x		x
Drinking water supply issues					x
Working in wet environments			x	x	x
Mosquito breeding habitat	x	x			

Based on the presentation of baseline risks and the WSSP process undertaken in each project community, 339 watershed interventions were prioritized for implementation across nine broad categories related to: animal management; drainage; health systems surveillance; integrated planning; land use management; sanitation systems; waste management; and water systems (Table 5). Interventions related to water systems were most frequently prioritized (29.2%), followed by land use management (21.5%). Priorities for water systems interventions related to needs for maintenance, repair and new infrastructure, as well as general awareness on the factors causing unsafe water and best practice related to water systems governance and management. Priorities for land use management were inclusive of: nature-based solutions, such as riverbank stabilization (i.e., with vetiver grass), reforestation, and forest protected areas; relocation of farms away from water sources; improved policy regulation with respect to development permitting and monitoring; and general awareness raising on agricultural best practices, forest ecosystem services, and fishpond management.

Table 5. Total number of watershed interventions prioritized by category as a result of baseline risk factor assessments and water and sanitation safety plan (WSSP) processes, compared with number of interventions implemented as of October 2022.

	Prioritized		**Implemented**	
	#	**%**	**#**	**%**
Animal management	47	13.9	8	5.2
Drainage	34	10.0	0	0.0
Health systems surveillance	3	0.9	11	7.1
Hygiene	11	3.2	16	10.4
Integrated planning	5	1.5	30	19.5
Land use management	73	21.5	22	14.3
Sanitation systems	29	8.6	0	0.0
Waste management	38	11.2	18	11.7
Water systems	99	29.2	49	31.8
TOTAL	339		154	

Implementation of interventions began in mid-August 2020, starting with the participatory WSSP processes in each community, which were counted under the integrated planning category. As of October 2022, 154 completed interventions were documented, the majority falling under water systems (31.8%), followed by integrated planning (19.5%), land use management (14.3%), waste management (11.7%), and hygiene (10.4%; Table 5). All 29 communities reported implementing watershed interventions on their own accord, while nearly 17% (26 of 154) implemented interventions were done so completely with human and financial resources from project partners, including government agencies, Water Authority of Fiji, and other NGOs (e.g., Rotary Pacific). Despite the high risks presented by large numbers of inadequately managed sanitation systems across all communities (Tables 3 and S2), needed sanitation interventions are yet to be undertaken due to procurement challenges partly due to a limited pool of experienced sanitation contractors. During follow-up monitoring, while the project team observed that some drainage issues identified were addressed by communities, these specific interventions have not yet been quantified through the iterative review of WSSPs.

Follow-up monitoring carried out between May and August 2022 indicated reduced risks in some communities against five specific risk factors that may at least partially be attributed to project interventions: environmental water quality (*E. coli*); primary drinking water source quality (*E. coli*), drinking water supply; piped drinking water quality (*E. coli*); and washing hands (Fig 3). Improvements to water infrastructure can lead to quick improvements in drinking water supply and quality, while awareness about best hygiene practice and distribution of soap, which was heightened due to community COVID-19 transmission, was likely responsible for the increased reported frequency of hand washing by food preparers. It is possible that fencing livestock away from rivers and primary water sources reduced faecal contamination in environmental and primary drinking water source water quality samples, though it is expected that impacts from other nature-based interventions (e.g., riverbank stabilization, reforestation) may take longer to yield impacts related to water quality improvements.

Fig 3. Examples of risks, interventions implemented to address each risk, and changes in the number of communities in each risk category between 2019 baseline and 2022 follow-up monitoring. Red = high risk; yellow = medium risk; green = low risk. Communities were assigned risk categories based on thresholds for each risk factor indicated in supplementary S1 Table.

Recognizing that gender roles shape the collection and use of water, and in response to recommendations from Nelson et al. [49] who suggested that water resource governance could be strengthened in WISH Fiji project communities by increasing representation of women and community health workers on water committees, the WISH Fiji project team made a concerted effort through our adaptive management cycle (Fig. 1) to facilitate more inclusive participatory planning in reviews of WSSPs and implementation of interventions. As a result, by October 2022, 69% of communities (20 of 29) increased representation of women on community water committees, and 83% of community water committees (24 of 29) included community health workers. Community health workers are community representatives trained by district health nurses to assist their communities to maintain proper child and maternal health and promote overall health and well-being. They work alongside the district health nurses to deliver community outreach and provide nurses with information regarding notable WASH issues requiring attention.

4. Discussion

4.1 Outcomes from a portfolio approach to integrated watershed management

WISH Fiji is a proof-of-concept project that has embraced a place-based, systems approach to health, building off principles identified in the Ottawa Charter for Health Promotion that recognizes the fundamental importance of supportive environments and the ability of people to self-determine health outcomes (see [2]). Watersheds offer a coherent and ecologically representative unit in which ecological foundations of health can be studied by examining anthropogenic drivers affecting critical ecosystem services, including clean water, natural hazard reduction, nutrition and regulation of disease transmission [3]. These drivers act within complex socio-ecological systems that are hierarchically scaled, composed of subsystems nested within larger systems [6]. Biotic elements within watershed boundaries typically share a more related environmental exposure history than those in separate watersheds, fostering increasing calls for “watershed epidemiology” to help link ecosystem and human health over broad spatial and temporal scales, inform environmental stewardship, and deliver a holistic model of watershed health [53].

Under WISH Fiji, our expectation, based on best available evidence from the literature [54, 55], is that a combination of nature-based solutions (e.g., forest protection, restoration around water sources, riverbank stabilization, coastal wetland management), WASH and behavior change interventions, implemented across nested scales within watersheds, will reduce the incidence of microbial disease in humans and aquatic organisms. We also hypothesize that upstream nature-based solutions that provide flood risk mitigation benefits (recognizing that these are variable, [56]), combined with other specific community and household-level interventions that reduce mosquito-breeding habitat (e.g., cutting bushes, eliminating standing pools, covering containers, improved solid waste management), will reduce incidence of dengue and other mosquito-borne illnesses [18].

Health systems surveillance data in Fiji, like many countries, are generally not geolocated to the residences of individuals presenting at health centers but are enumerated by health facilities [18]. As a result, we are challenged with an inability to link specific watershed socio-ecological variables and management actions to specific disease incidence because health facilities in Fiji generally do not record the home address of those visiting the facility. We attempted to overcome this under WISH Fiji by asking about suspected case incidence and reviewing hospital and rural health clinic records for confirmed case incidence. These investigations yielded very low case numbers, likely to the limitations of our project geography and many confirmed cases not being geolocated. New opportunities are emerging with the use of digital platforms to link disease clusters to place-based factors [57-59]. However, ethics considerations of digital surveillance need more scrutiny, and the technological innovations may not necessarily be suitable for remote locations where people are not connected online or resolved at fine enough geographic scales for smaller watersheds. In the absence of confirmed and reliable case data collected within watershed boundaries to enable identification of key local drivers of disease risk, and as described above, the WISH Fiji approach has been to measure a suite of potential risk factors and then co-design portfolios of interventions with communities and partners based on these measured potential risks to improve systems health (Fig 1).

Through WISH Fiji, we confirmed that watershed-level characteristics are important in most communities in all sub-catchments. Soil erosion associated with rainfall and/or poor land use practices changes hydrological and water quality characteristics downstream [60, 61]. These disturbances influence more proximal determinants of human health, like access to clean water, habitat for mosquito vectors that carry disease like dengue, and direct exposures to contaminants and infection [24]. Similarly, a high amount of high flood risk area in the sub-catchment poses a risk for exposure to: zoonotic disease like leptospirosis, which can be transmitted through mammalian urine and excreta that are mobilized by flood waters [31]; and bacterial disease like typhoid which is transmitted through faecal-oral pathways [11]. Flood risks and rainfall-associated erosion are likely to accelerate under predicted future climate scenarios for Fiji, with high probability of greater intensity and frequency of days of extreme rainfall [62]. Perceptions of frequent flooding were recognized by householders in our surveys, suggesting that interventions around placement of future houses constructed in communities may not be difficult to implement. In both cases, more careful planning at the village and district level about the placement of communities and houses on tenured land is a warranted intervention.

We found an almost universal need for improvement of sanitation back-end infrastructure so that faecal sludge is safely contained or treated [63]. This is not uncommon in rural communities in low to medium income countries, where there are documented links to unsafely managed sanitation and poor human health [14]. In Fiji, inadequate placement and upkeep of sanitation facilities will increase the likelihood of exposure in downslope communities and contamination of waterways downstream. Identifying the highest priority (most damaged, most poorly placed) latrines continues to be an important part of the WSSP process and intervention activities for WISH Fiji. Also at the community-level, primary drinking water sources were nearly always from spring-fed dams, from which piped water was drawn to reservoir tanks and then delivered to households. The land surrounding springs is rarely protected from human activity and livestock incursion, and there is a distance between the spring and the dam where faecal contamination can easily occur. Increased risks of exposure to faecal pathogens from drinking water supplies have been documented to occur in other tropical, rural settings due to unimproved drinking water infrastructure and the use of surface water (rivers or creeks) as an alternate drinking water source [64]. All of these matters provided us with opportunities for cost-effective interventions for systems health outcomes.

Finally, we found patterns of risk factors related to behaviours of residents, including reporting infrequent hand washing (and/or without soap) and high frequency of working in wet environment (including without appropriate protective equipment). Under these circumstances, awareness raising, education and health promotion activities are worthy interventions in rural communities in Fiji where mosquito habitat remains in proximity to households [18], where exposure to contaminated water in the environment is likely to occur [65], and where increased attention to hygienic practices are warranted [66].

Interventions will change risk at different spatial and temporal scales and will have variable impacts across geographic and socio-economic contexts [56]. For example, evidence indicates that changes in water quality, including bacteria levels, post-wastewater management and water infrastructure improvements can occur in as little as one to two years [67], whereas ecosystem-level changes in downstream communities in response to upstream interventions, particularly from restoration, are more likely to require decadal timescales for recovery [67, 68]. The time lag from intervention planning to response is also influenced by the complexities of land tenure in Fiji. For instance, engaging in forest restoration is complex, requiring mapping erosion-prone areas near water sources, identifying and verifying rightful landowners, and only then sourcing or growing of seedlings for outplanting once landowner consent is granted – a process which may on its own take well over a year to achieve.

While we observed fewer communities in higher risk categories post-interventions related to adequacy of drinking water supply, source, piped and environmental water *E. coli,* and frequency of handwashing, we acknowledge that there was not a lot of time between implementing interventions and follow-up monitoring to affect change. We also did not have enough time to complete interventions targeting all high-risk factors, especially for sanitation systems. Differences in risk factor measurements post-interventions could also be a result of: natural stochasticity, sampling variability and seasonal/climate differences (e.g., for environmental water quality); different individuals responding as heads of households; influence of COVID-19 hygiene messaging or respondents telling us what they think we want to hear (e.g., for handwashing); or other activities happening within the communities of which we are not aware.

Given that interventions within the project are delivered as a portfolio of actions across multiple nested scales, tools are needed to quantify the risk reduction potential of the combined effect of these interventions. Bayesian Belief Networks (BBNs) are one increasingly popular analytical platform that can incorporate knowledge of different uncertainties, from different scales and sources, and easily handle missing data [69-71]. Using BBNs can help identify co-benefits across and within nested scales and where simultaneously implementation of multiple interventions across different scales could have a larger effect than the complete reduction of risk factors at any one level [72]. Using decision-support tools such as BBNs does not, however, eliminate the need to balance trade-offs in different aspects of systems health: for example, proximity of swamps may increase risk of vector-borne disease such as dengue, while at the same time the wetlands provide important ecosystem services for flood mitigation and nutrient cycling that may reduce risk from pathogenic bacteria and other contaminants to people and ecosystems downstream [73, 74].

Intervention planning ultimately needs to take into consideration these trade-offs and balance risks, particularly with attention to what interventions can produce the most net improvements for overall systems health.

4.2 Lessons for knowledge co-production within research-action arenas

The collaborative and cross-sectoral nature of project implementation allowed the WISH Fiji team to leverage unanticipated outcomes that support long-term durability of the approach. The co-produced WSSPs for each community were supportive in several ways that enabled external partners from NGOs and government to directly contribute to intervention implementation in project communities. First, priorities from the WSSPs were integrated into broader Integrated Village Development Plans, which form the basis for annual resource allocation at the provincial level. Secondly, through co-development of WSSPs with communities, government and staff from the Water Authority of Fiji (WAF), community leaders became better aware of the process for notifying WAF of priorities for water infrastructure improvements, which involves raising the issues at provincial meetings so that they can be reported to WAF for inclusion in annual budget allocation. These actions became increasingly important as WISH Fiji project staff were unable to access project sites for lengthy periods due to COVID-19 related restrictions on movement in Fiji.

WISH Fiji also played an important convening and brokering role to bring important sectoral actors together (i.e., from ministries of Health, Rural Development [Department of Water and Sewerage], Forestry, Agriculture, Environment, iTaukei Affairs, and WAF) for joint stakeholder planning at the district level. The WISH Fiji Catchment Coordinators were responsible for leading facilitation, documentation and educating participants about potential impacts and synergies of each sector's planned local activities. This type of cross-sector coordination and collaboration can improve efficiency of resource allocation and minimize implementation of actions that too narrowly focus on single-sector strategic objectives at the expense of overall systems health [34, 75]. Such brokering, intermediary and boundary spanning roles are increasingly recognized as essential components of successful interdisciplinary and cross-sectoral collaboration [76].

5. Conclusion

The 2050 Strategy for the Blue Pacific Continent, endorsed by Pacific Island Forum Leaders in July 2022, has a goal for people-centred development that "All Pacific peoples continue to draw deep cultural and spiritual attachment to their land and ocean and all are assured safety, security, gender equality, and access to education, health, sport and other services so that no one is left behind." While broad in scope, the goal places emphasis on the connections between people and place, and how this underpins health, both fundamental dimensions of Pacific Islander perspectives of well-being [37]. The WISH Fiji project firmly aligns to this strategy by promoting systems health within a watershed unit to enable attention to environmental drivers of ill-health at the scale at which ecological processes occur within water basins. The four-year, proof-of-concept project has documented the potential to improve systems health through coordinated interventions across nested scales that simultaneously address critical risks from poor sanitation infrastructure, water supply systems, land use practices, waste management, animal management, drainage, and basic hygiene. However, full realization of the WISH approach to effectively reduce disease risk will require further systems transformations. Effective watershed management requires long-term investment across large scales. Sustainable financing mechanisms, such as water funds or other environmental funds are needed [6, 77], coupled with the appropriate institutional architecture to distribute funding to and coordinate interventions in high-risk areas. Improvements in health systems surveillance are also required: it is not possible to relate spatial drivers of disease incidence to case incidence and/or effectiveness of place-based interventions unless case data are geolocated to place of residence. With increasing population pressure, landscape modification and climate change impacts that promote disease risk, there is increasing urgency to make the necessary institutional and governance changes required to secure the health and well-being of Pacific Island communities.

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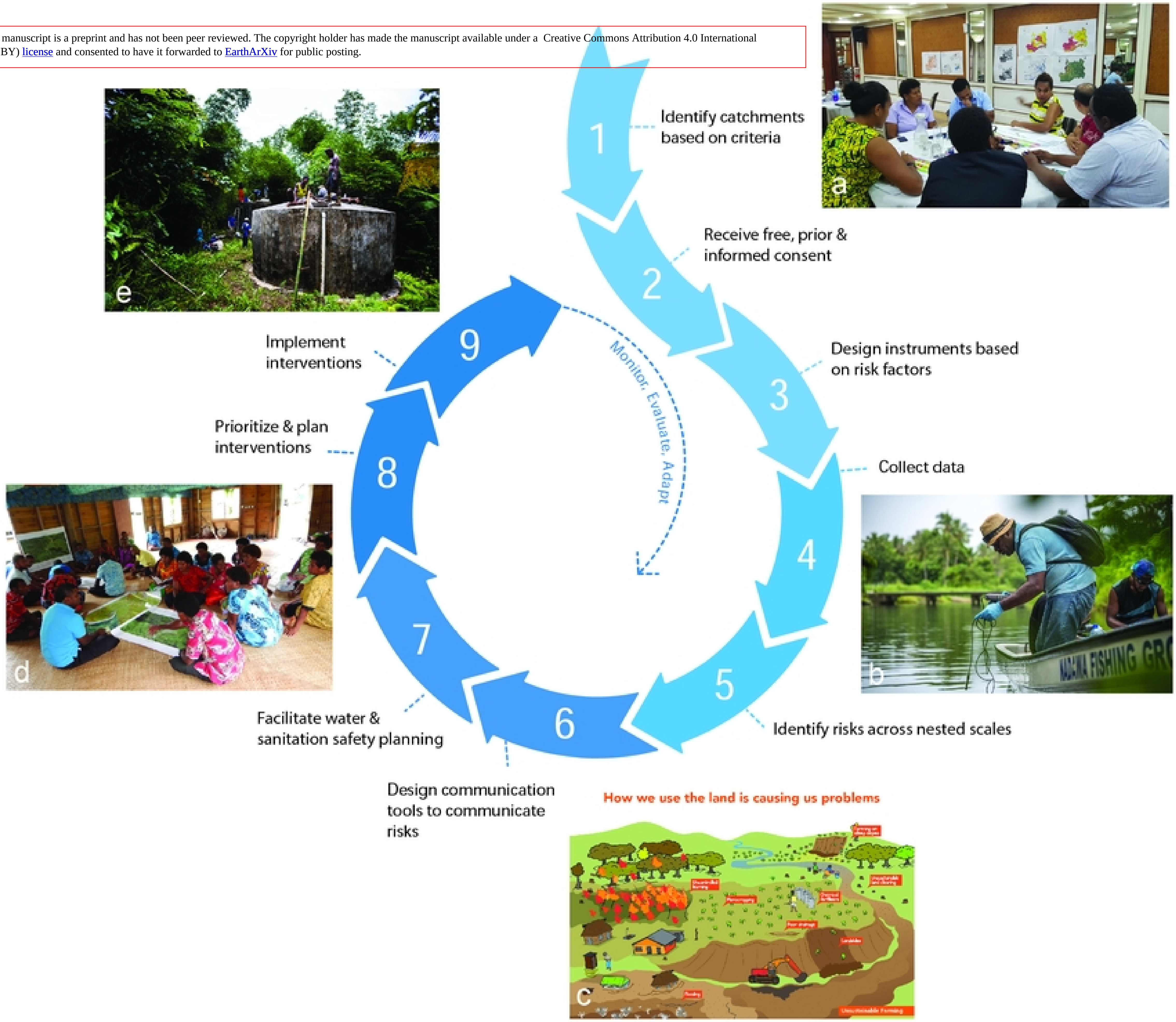
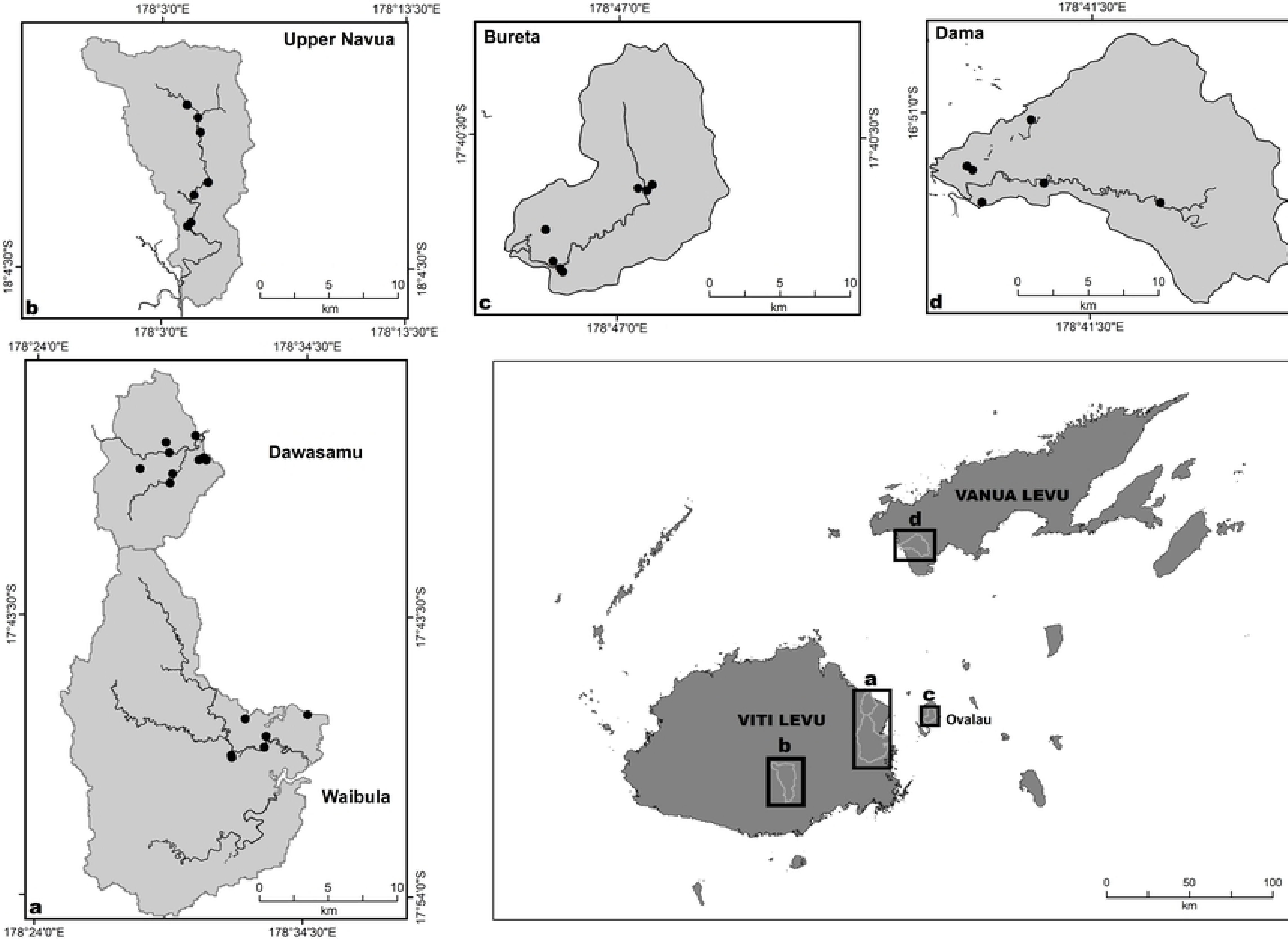
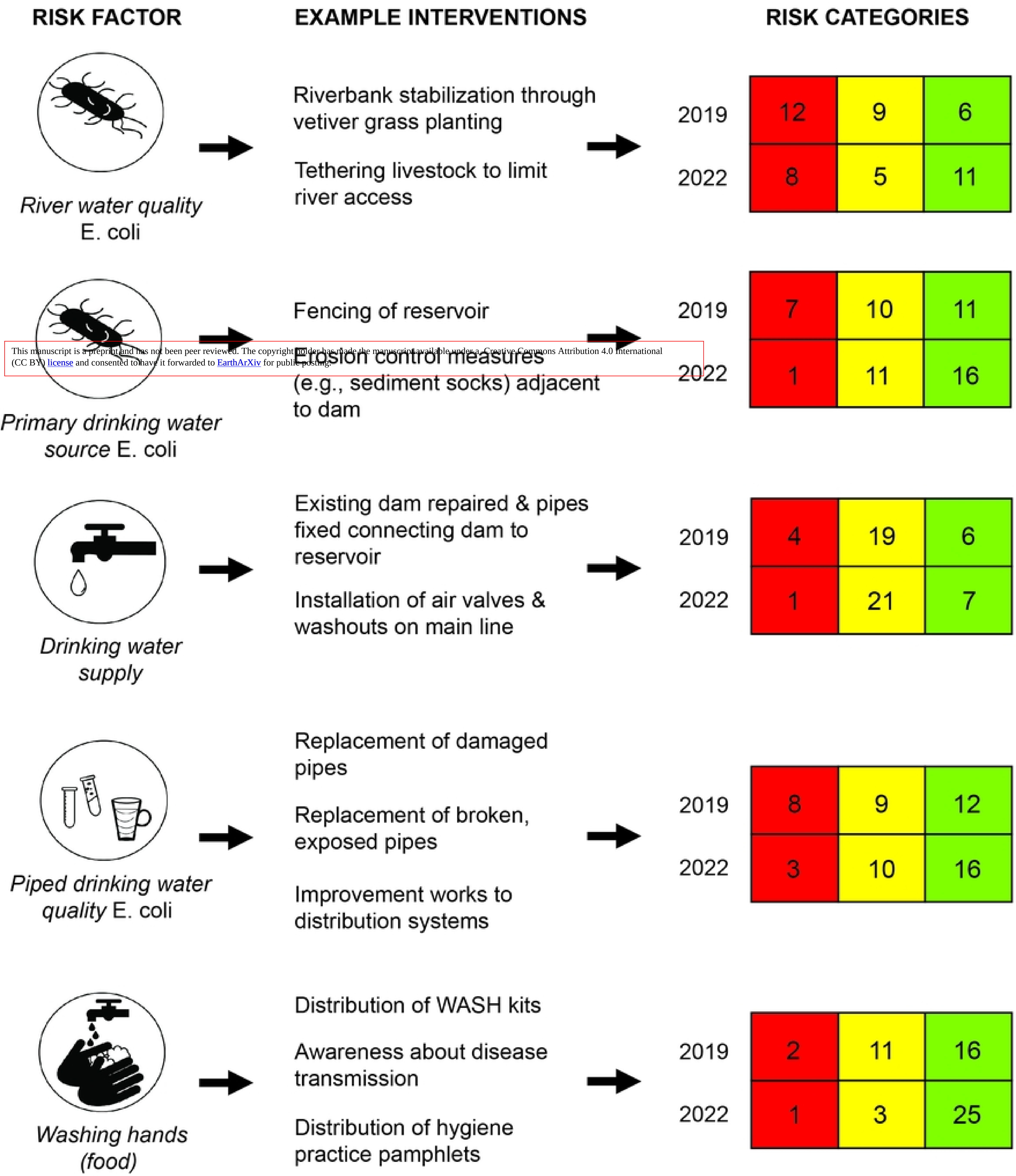

1
Identify catchments based on criteria
2
Receive free, prior & informed consent
3
Design instruments based on risk factors
Collect data
4
5
Identify risks across nested scales
6
Design communication tools to communicate risks
7
Facilitate water & sanitation safety planning
8
Prioritize & plan interventions
9
Implement interventions
Monitor, Evaluate, Adapt
a
b
How we use the land is causing us problems
c
d
e

Figure


Upper Navua
178°3'0"E
178°13'30"E
18°4'30"S
0
5
10
km
b
Bureta
178°47'0"E
17°40'30"S
c
Dama
178°41'30"E
16°51'0"S
d
178°24'0"E
178°34'30"E
17°43'30"S
17°54'0"S
Dawasamu
Waibula
a
VANUA LEVU
VITI LEVU
Ovalau
50
100

Figure


RISK FACTOR
EXAMPLE INTERVENTIONS
RISK CATEGORIES
River water quality
E. coli
Riverbank stabilization through vetiver grass planting
Tethering livestock to limit river access
2019
12
9
6
2022
8
5
11
Primary drinking water source E. coli
Fencing of reservoir
Erosion control measures (e.g., sediment socks) adjacent to dam
2019
7
10
11
2022
1
11
16
Drinking water supply
Existing dam repaired & pipes fixed connecting dam to reservoir
Installation of air valves & washouts on main line
2019
4
19
6
2022
1
21
7
Piped drinking water quality E. coli
Replacement of damaged pipes
Replacement of broken, exposed pipes
Improvement works to distribution systems
2019
8
9
12
2022
3
10
16
Washing hands (food)
Distribution of WASH kits
Awareness about disease transmission
Distribution of hygiene practice pamphlets
2019
2
11
16
2022
1
3
25

Figure