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Temporal and thematic trends in water, sanitation and hygiene (WaSH) research in Pacific Island Countries: A systematic review

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Short title: Review of WaSH research in PICs

ABSTRACT

Pacific Island Countries (PICs) lag behind global trends in water, sanitation and hygiene (WaSH) development. We conducted a systematic search of all English language papers (published before February 2015) about WaSH in PICs to evaluate the state of the peer-reviewed literature and explore thematic findings. A total of 121 papers met the criteria for full-text review following an initial search result of more than 6000 papers. Two reviewers independently assessed the quality and relevance of each article and consolidated their findings according to four emergent themes: public health, environment, emergency response and interventions, and management and governance. Findings indicate a knowledge gap in evidence-guided WaSH management strategies that advocate for human health while concurrently protecting and preserving drinking water resources. Extreme weather events threaten the quantity and quality of limited freshwater resources, and cultural factors that are unique to PICs present challenges to hygiene and sanitation. This review highlights the strengths and weaknesses of the peer-reviewed literature on WaSH in PICs, addresses spatial and temporal publication trends, and suggests areas in need of further research to help PICs meet development goals.

Keywords: Development goals, disaster relief and response, environmental health, public health, Small Island Developing States (SIDS), water resource management

INTRODUCTION

The public health, economic and educational benefits of adequate water, sanitation and hygiene (WaSH) are clear and substantial (Bartram & Cairncross 2010). Between 1990, the baseline of the Millennium Development Goals (MDGs), and 2015 over two billion people have gained access to improved sanitation, and two billion also to improved drinking water. Despite this global progress, the Pacific

Island Countries (PICs), are lagging with 44% of the population relying on unimproved drinking water, and 65% using unimproved sanitation facilities (UN 2015).

The challenges associated with the implementation, and ultimately the success (or failure) of WaSH services in PICs are well-known from a practical perspective. The often-stated obstacles to improving WaSH services relate to the remoteness of communities, capacity constraints (at government and community levels) and political instability. There have also been concerns raised about the lack of contextual information and awareness in the planning of WaSH services, including a lack of participation and inclusion of gender and minority groups and insufficient social, cultural and environmental knowledge guiding decision-making. These predispose development projects to failure in implementation and insufficient uptake of improved WaSH services (Clarke et al. 2014). The PICs also face the challenge of extreme weather events that frequently damage water and sanitation infrastructure, and threaten the sustainability of development programmes. They are on the frontlines of climate change (Farbotko 2010), where rising sea levels, increasingly variable precipitation patterns and changing storm frequencies and magnitudes increase complexity in delivering and maintaining access to improved WaSH (Meehl & Washington 1996; Hadwen et al. 2015).

While there has been some effort to examine the performance and efficacy of WaSH strategies in the PICs (Bain et al. 2014; Clarke et al. 2014), there has not been a systematic evaluation of the peer-reviewed literature about WaSH across the region. In light of the limited progress made towards achieving the MDGs, there is a need for the synthesis of published papers assessing the context-specific public health risks linked to WaSH, the usefulness of different intervention technologies and programs, careful consideration of environmental hazards, management and governance of both human and natural resources, and a better understanding of the broader topics associated with the physical and cultural settings unique to PICs.

We evaluated the peer-reviewed literature about WaSH in the PICs through a wide lens to capture the impacts of WaSH on the environment and vice versa, as well as the reported impacts of different methods of governance on WaSH service delivery and resource management. Our aim is to inform future WaSH research in the PICs, by identifying areas of strength and weakness in the evidence-base to improve access to safely managed drinking water and sanitation, as part of goal six of the Sustainable Development Goals (SDGs) (Wallace & Bailey 2015; WHO et al. 2016). A thorough analysis of the state of knowledge around WaSH within the specific socioeconomic, cultural and environmental context of PICs is needed to establish the degree to which progress and improvements in WaSH services might be either currently limited, or potentially enhanced, by our understanding of the systems and the behaviours of the local contexts where WaSH service provision is needed. In light of these factors, our review had three objectives:

1. To review and report the state of peer-reviewed research of water resource management and WaSH in the PICs.
2. To explore trends in peer-reviewed WaSH research activity across PICs and through time.
3. To identify emergent themes within the peer-reviewed literature and establish areas in need of greater research.

METHODS

We reviewed WaSH research published in academic journals using the PRISMA guidelines for systematic reviews and meta-analyses (Moher D et al. 2009), with specific attention to PICs. Searches were performed using a combination of twenty geographic (i.e. country and regional) names, eight WaSH (e.g. drinking water, toilets, hygiene) and seven human health (i.e. disease and pathogen names) terms for a total of 1,280 combinations (supplementary Table S1). Our literature search uncovered a myriad of studies ranging from household water treatment to climate change policy with vastly different outcome

measures, making meta-analysis infeasible (Table 1). Public health studies generally applied epidemiological and microbiological analyses to uncover disease transmission and prevalence, while environmental studies explored freshwater availability and concentrations of chemical and biological pollutants. Intervention and adaptation studies investigated the effectiveness of WaSH improvement projects, or the impact of disaster response actions. While papers sometimes used similar indicators, for example for biological water quality, they were used in different ways to study different relationships in the three themes. Similarly, some relationships studied in WaSH management and governance research employed sociological measures similar with those found in intervention and adaptation studies but the associated interviews and group discussions had different purposes. Meta-analysis was therefore inappropriate for our goals. Therefore, this review employed a narrative synthesis of public health, the environment, emergency WaSH and intervention strategies, and management and governance insofar as they related to WaSH research in PICs. Given the heterogeneity of the parameters studied and the topics covered in this review, two authors independently assessed each paper for quality of scientific study and the implications for WaSH in PICs. Each of the two authors assigned to a specific topic then consolidated their findings in a qualitative review of emergent themes.

Table 1. Common metrics used in water, sanitation and hygiene research about Pacific Island Countries, organized by thematic trends.

Thematic Section	Thematic Sub-sections	Most common metrics (# papers using metric)
Public Health	Animal husb./zoonosis	Leptospirosis (3), parasites (2), brucellosis (1), pigbel (1)
	Personal hygiene	Typhoid (3), cholera (3), yaws (2), diarrhoea (1), handwashing (1)
	Seasonal variability	Diarrhoea (3), coliforms (1), melioidosis (1), burkholderia pseudomallei (1)
	Sanitation	E. coli (3), cholera (3), diarrhoea and dysentery (2), heavy metals (1), typhoid (1)
Environment	Atoll freshwater lenses	Lens thickness (7), salinity (2), chloride (2), electrical conductivity (2), pumping capacity/sustainability (2), drainage rate (1)
	Radioactivity/nuclear testing	Transuranic radionuclide inventory (2), dose equivalent rate (2)
	Saline intrusion	Electrical conductivity (3), salinity (2)
	General pollution	Heavy metals (3), nitrates/nutrients (3), pesticides (2), faecal coliforms (2), E. Coli (2), fluoride concentration (1), detention pond size (1), total waste produced (1)
	Sanitation	Faecal coliforms (4), E. coli (3), diarrhoeal prevalence (2), enterococci (1), Vibrio cholera (1), toilet density (1)
Interventions and Adaptation	Water sources	Water quality measures (10), E. coli (5), model development (4), community values (3)
	Disaster response and recovery	Community values (4), water quality measures (4), damage assessment (2), sanitation practice (1), model development (3)
	Monitoring and evaluation	Evaluation of interventions (5), water quality measures (3), community values (4), model development (1)
Management and Governance	Implemented changes	Human resources (4), financial resources (6), governance arrangements (12)
	Context	Integrating indigenous knowledge (4), locally appropriate technologies (2), context-appropriate approaches (20)
	Participation	Stakeholder participation (2), community participation (10), community education and awareness (5)
	Use of data	Data to guide planning (6), long-term impacts of development (2), catchment-scale planning (3)

Literature Search

We searched three online databases of peer-reviewed journals (Web of Science, IWA Publishing and Pub Med) for articles published in English. The search had no date restrictions and was conducted between September 2014 and February 2015.

Screening and Eligibility Assessment

After an initial screening of title and keywords (MCM), two reviewers independently screened the abstract of all remaining studies (MCM and TC). Abstracts with explicit reference to any element of water, sanitation or hygiene were immediately accepted for further review. Abstracts were screened against criteria in Table 2 to ensure relevance to WaSH, PICs and human health.

Table 2. Criteria for Abstract Screening

Environment/Weather	**Health**	**Hydrology/Geography**	**Behaviour**	**WaSH***
Storms	Diarrhoea‡	Stream flow/health	Traditional practice	Sewage
Droughts	Pathogens	Soil leaching/contamination	Environmental management	Solid waste disposal
Tsunamis	Enteric infection‡	Reservoirs/dams/channels/etc.	Integrated water resources management (IWRM)‡	Drinking water
Earthquakes	Disease outbreak‡	Groundwater/lens/water table/infiltration/etc.	Safety	Water treatment
Floods	Skin infection		Embarrassment	Handwashing
Disasters (general)	Dental caries/rot/infection		Disaster preparedness	Toilets
Rainfall	Trachoma/ eye infection		Water safety plans‡	Defecation
Pollution (chemical, biological, etc.)	Child morbidity/mortality			Sanitation
Coliforms				Faeces
E. coli				Hygiene

***** Abstracts that explicitly refer to any aspect of WaSH were included, and did not require a second inclusion term.
‡ These inclusion terms are integral to WaSH; therefore, abstracts referring to these topics were included without the need of a second search term.

Articles were included in one or more of the following thematic categories identified during abstract screening and independently reviewed by two authors: public health (reviewing authors: MCM and ME), environment (TC and DJB), emergency WaSH and intervention strategies (WH and AK), and management and governance (KFS and RTS). The two reviewers independently read and screened each full length paper before reaching consensus on whether to include it in the review, using the same criteria as the abstract screening (Table 2).

RESULTS

Search Results and Study Characteristics

A total of 6,244 references were identified, 2,265 were eliminated as duplicates, and 3,268 were eliminated on the basis of title and keywords. Of the remaining 711 studies, 205 were considered eligible for full text screening based on abstract screening. Full text could not be found for 36 of these records, and an additional 84 papers were omitted because they did not satisfy the inclusion criteria based on full text review (Figure 1).

Of the 121 studies included, 100 (82.6%) were water-related, 54 (44.6%) sanitation-related, and 30 (24.8%) hygiene-related. Combined topic papers, reporting on more than one element of WaSH were common, with 29 (24.0%) studies on water and sanitation, three on water and hygiene (2.5%), three on sanitation and hygiene (2.5%), and 19 (15.7%) studies presenting a general discussion of WaSH with references to more than two topics. Many of the studies included both rural and urban settings (n = 52, 43.0%); however, studies that covered only rural (n = 45, 37.2%) WaSH conditions greatly outnumbered those that only covered urban (n = 20, 16.5%) WaSH conditions. Informal and peri-urban settlements received less attention, with mention in 17 (14.0%) and 20 (16.5%) studies, respectively, with 15 (12.4%) of these studies discussing both types of settlements.

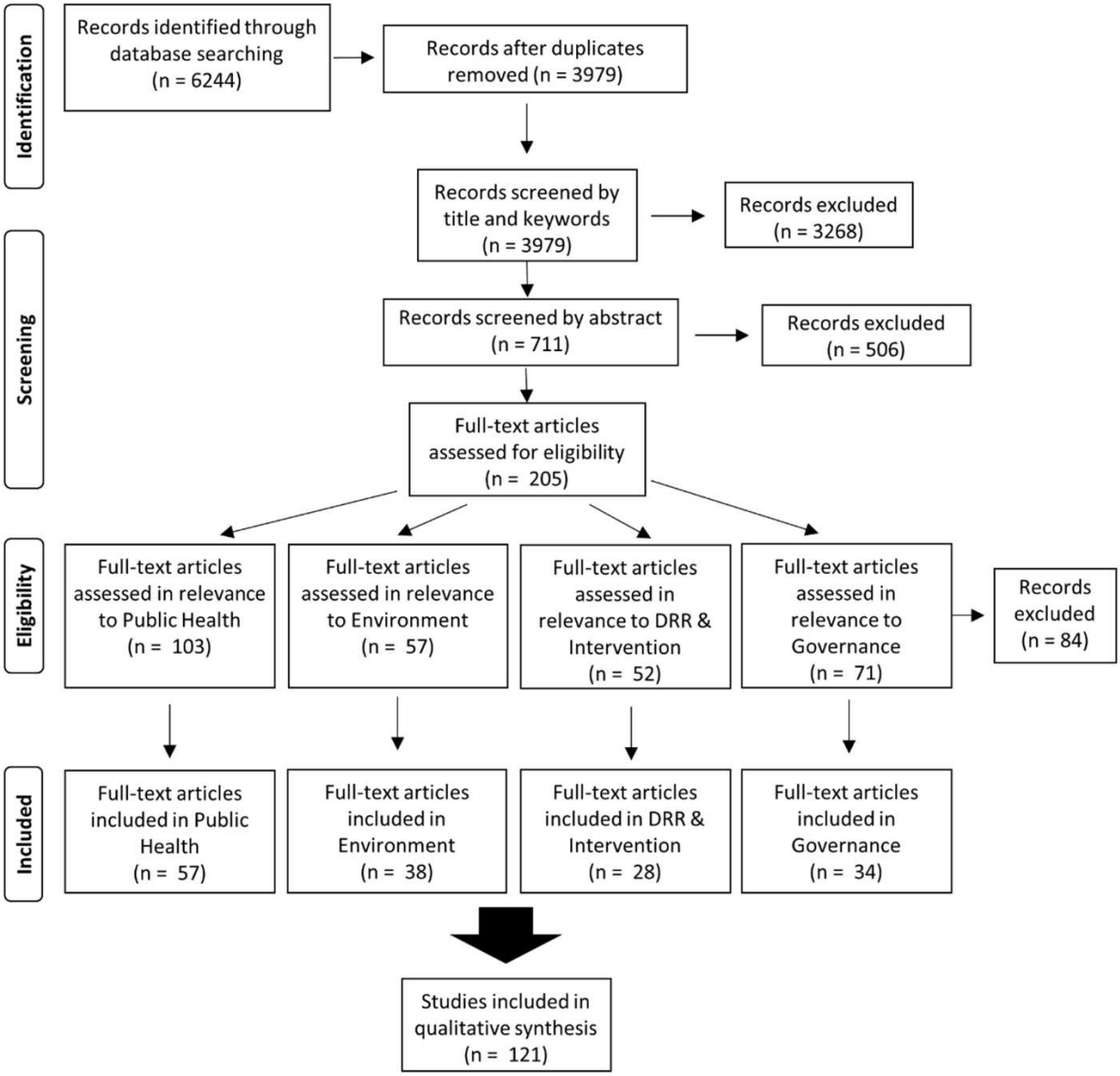

Figure 1. Breakdown of literature search and screening process for WaSH research in Pacific Island Countries using the PRISMA flowchart for systematic reviews (adapted from Moher D et al. 2009, and Wallace & Bailey 2015). The sum of papers included in each thematic category does not equal the total number of paper reviewed because some papers were assigned to more than one category.

Temporal trends in WaSH publications

Between 1955, the year McCarthy et al. published a study on sanitation and intestinal parasites in Western Samoa, and 1975 there were only five peer-reviewed publications involving WaSH in PICs. Nineteen studies were published between 1975 and 1990 (five every four years), a rate which more than doubled between 1990 and 2000. This again more than doubled with an average of over six publications per year, for a total of 103 peer-reviewed studies published between 2000 and 2015. It is difficult to determine precisely what caused these intensifications in scientific effort, as there are numerous possible explanations. For example, the increases observed in 1990 in public health and the environment coincide with the UN Summit for Children, and the increase in management and governance shortly after the year 2000 roughly coincide with the UN Millennium Declaration; however, we offer these examples as two of many possible explanations. Studies on management and governance have markedly increased relevant to other thematic categories since 2005, while studies on public health and the environment are most numerous (Figure 2).

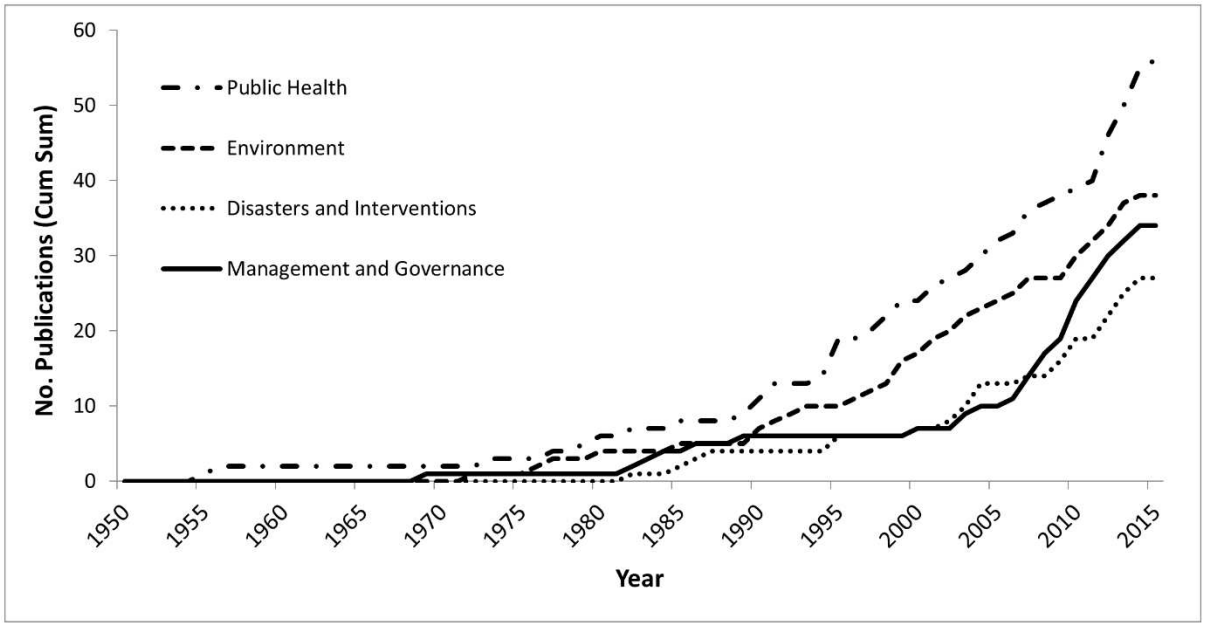

Figure 2. Temporal publication trends of water, sanitation and hygiene research in Pacific Island Countries by theme areas.

Spatial trends in WaSH publications

With over 42% of all peer-reviewed WaSH research occurring in Papua New Guinea (PNG), Fiji and Kiribati there was a spatial bias in the PICs literature. Conversely, there were no peer-reviewed research articles for the Marianna Islands, Niue or Tokelau (Figure 3). In PNG, the most common theme of study was public health, particularly investigations of epidemics of cholera and typhoid. In Fiji and Kiribati, the research focus was weighted towards management and governance, with particular attention paid to water service delivery.

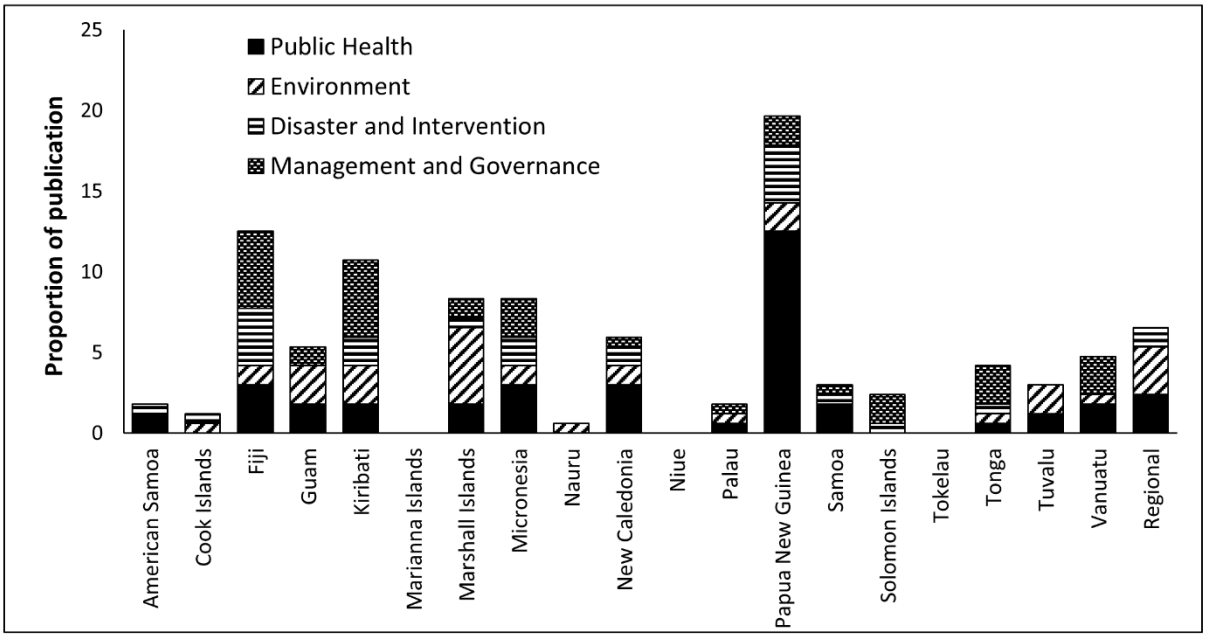

Figure 3. Number of publications for individual Pacific Island Countries on water, sanitation and hygiene, showing the proportion of publications by country, and the distribution of publications across the themes of this review.

Trends and issues by thematic area

Public Health

Most public health studies fit into four categories: linking disease prevalence with animal husbandry and zoonotic pathogens (Owen 2005; Berlioz-Arthaud et al. 2007; Guerrier et al. 2013), personal hygiene (Larsen 1995; Tran et al. 2006; Greenwell et al. 2013), seasonal variability (Warner et al. 2007; Perez et al. 2011; Choudhary et al. 2012), and poor sanitation (Bukenya & Nwokolo 1991; Horwood & Greenhill 2012; Fujita et al. 2013).

The domestication of pigs and their proximity to community water sources is associated with the incidence of leptospirosis (Lau et al. 2012), which is transmitted by contact with acutely infected animals or exposure to soils or freshwaters containing the urine of carrier animals (Berlioz-Arthaud et al. 2007). Vulnerability to zoonotic infections may increase in PICs by inadequate food hygiene and unsafe cooking practices. Pigbel, also called enteritis necroticans, a bowel infection caused by Clostridium perfringens, is a swine-related zoonotic infection contracted by the ingestion of contaminated and undercooked meat (Murrell & Walker 1991). Similarly, contracting brucellosis, caused by Brucella bacteria, is a particular concern in PICs where undercooked meat is popular (Guerrier et al. 2013). While pig rearing has become a pillar of food security and income generation in many PIC communities, it simultaneously presents a substantial public health risk (Owen, 2005), with a strong need for community-led initiatives to manage pig faecal waste and protect the quality of surrounding water resources (Terry & Khatri 2009). While this threat to public health has been acknowledged in peer-reviewed literature, specific investigation into safer rearing practices and the protection of freshwater sources from animal faeces was found to be lacking.

Handwashing and good food hygiene are well-known to prevent diarrhoea (Jenkins 1995; Larsen 1995); however, we found no mention of research into the prevalence of or the barriers to handwashing in PICs. In addition to limited water availability due to seasonal precipitation patterns (Kostyla et al. 2015), cultural practices deserve greater attention. For example, the ‘extra hands’ involved in communal cooking

at festivals and social gatherings increase the likelihood of food contamination, including contamination with bacterial pathogens that may multiply during inadequate food storage (Bukenya & Nwokolo 1990). In PNG, the spread of cholera between relatively isolated communities has been linked to hygiene and person-to-person contact (Rosewell et al. 2012), including the traditional funeral practice of touching ones' deceased, which has been condemned for its capacity to spread bacteria and prolong disease outbreaks (Horwood et al. 2014).

Large storms threaten public health in PICs when WaSH infrastructure is overwhelmed by high-tides and torrential rains that also contaminate freshwater with raw excreta (Mosley et al. 2004). The rainy season was found to coincide with peak prevalence of infections including Salmonella spp. and Shigella spp. (Germani et al. 1994), and melioidosis, caused by a bacterium (Burkholderia pseudomallei) common in native waters and soils (Warner et al. 2007). Conversely, high temperatures and limited rainfall have also been linked to increased enteric infection (Wyrsch et al. 1998; Singh et al. 2001). In some PICs, water shortages during dry periods may trigger conservative usage where consumptive needs are prioritized over handwashing, increasing person-to-person disease transmission. Household water management in PICs and how uses are prioritized during environmental extremes has been found to be a knowledge gap in the peer-reviewed literature (MacDonald et al. 2016).

The evidence suggests a complex interaction of social and biophysical factors that contribute to infectious disease during dry and rainy seasons. Whilst the epidemiology of specific diseases may be seasonal, there is evidence to suggest that some pathogenic microorganisms exist in the natural environments of PICs. Faecal indicator bacteria, such as Escherichia coli and Enterococcus spp., are found in the natural soil environments of tropical countries, rendering them imperfect indicators of faecal pollution used to establish regional water quality standards (Fujioka et al. 1999; Fujioka 2001). Health studies in PICs that build hypotheses around water quality using these indicators should be interpreted accordingly.

Environment

Many peer-reviewed articles linked the impact of human WaSH activities on the environment, or the impact of environmental factors on human WaSH activities in PICs. Some acknowledged the connectivity between humans and the environment (Merson et al. 1977; Singh et al. 2001), although in most cases this had to be inferred by the reader. Across the literature, there was a disproportionate focus on links between WaSH and the environment which are novel to researchers from outside the region. For example, of the eight WaSH-environment studies of the Marshall Islands, four focused on the impact of nuclear testing on atoll freshwater lenses. This focus may be the reason for the lack of investigation into the linkages between WaSH and the environment in geomorphologies which are less unique to the PICs (e.g. floodplains).

The literature linked various environmental factors to the reduction in the volume of freshwater lenses that is suitable for human use. Most of these factors are influenced, or caused, by human activities, although that was rarely discussed in the reviewed literature. Papers discussing the link between freshwater lenses and WaSH focused on excessive or inappropriate methods of water extraction (Ghassemi et al. 1990; Griggs & Peterson 1993; Koda et al. 2013), climate change (Storey & Hunter 2010; Terry & Falkland 2010; Nakada et al. 2012), drought (Terry et al. 2001; White et al. 2007; Bailey et al. 2013) and saline intrusion (Ghassemi et al. 1990; Griggs & Peterson 1993; Koda et al. 2013). Given the nuclear testing which took place on the Marshall Islands between 1946 and 1958, several articles addressed the impact of radioactive waste on freshwater lenses (Noshkin & Robison 1997; Robison & Noshkin 1999; Davisson et al. 2012). In contrast, few considered other freshwater source types, such as surface water and rainfall (van der Velde et al. 2007; Storey & Hunter 2010; White & Falkland 2010).

Environmental pollution, especially from sanitation (Duwig et al. 1998; Wen 2011; Fujita et al. 2013) and solid waste management (Carden 2003), received some attention in the literature. Bottomless septic tanks and pit toilets have been implicated in faecal pollution (Fujita et al. 2013; Fujita et al. 2014), although

there was little research on the environmental impacts of open defecation, a common practice in many PICs. Only three published studies were found that specifically explored the link between sanitation and environmental contamination (Fujita et al. 2013, 2014; Merson et al. 1977). Each study had a different location and focus (faecal contamination, heavy metals and cholera) providing a limited evidence base given the importance of this link to human health.

Pollution of drinking water sources by mechanisms unrelated to sanitation and environmental hygiene has been explored, particularly natural soil and volcanic action (Ohtsuka et al. 1985; Fujioka et al. 1999; Cronin & Sharp 2002) and agricultural chemicals (van der Velde et al. 2007; Wen 2011). However, more information is needed on improving water quality damaged by these factors (Heitz et al. 2000).

Many of the articles on WaSH management and governance had specific recommendations for improvement. However, these are often not widely applicable, as they are derived from modelling of specific situations (Terry et al. 2001; Terry & Falkland 2010), technologies (Koda et al. 2013), geological formations (Nakada et al. 2012) or communities and regions (Thomas 2003; Wohl 2006). There was minimal discussion of the social factors affecting environmental management, which were of great importance in the PIC context (Guerrier et al. 2013; Clarke et al. 2014). Indeed, even though many studies mentioned the environmental and cultural heterogeneity of the PICs (South et al. 2004; White et al. 2007; White & Falkland 2010) these scientific studies are not in a form that makes findings transferable and there remains a lack of knowledge with respect to how to place specific findings into other contexts or even other PICs. The importance of understanding local environmental, social and cultural values cannot be overstated in terms of achieving intervention success. The temptation here is to evaluate the degree to which potential interventions may be scaled up, to be implemented across multiple communities. However, given the socio-cultural heterogeneity in the Pacific, it is more important to consider the need to adopt a transferable process, whereby communities are deeply engaged in WaSH intervention projects, before, during and after implementation. In this sense, successful intervention is less

about the specific intervention involved (although that obviously does play a role) and more about the participatory involvement and understanding of social, cultural and environmental values of the people in the community.

Emergency WaSH and intervention strategies

Many WaSH interventions reported in the literature are responses to extreme weather (floods, droughts and cyclones) or damage to WaSH services, with the vast majority focusing on the immediate delivery of safe water supplies to affected communities (Finau et al. 1986; Mosley et al. 2004; White et al. 2007). Others concern tectonic events like earthquakes that cause tsunamis (Dengler & Preuss 2003; Choudhary et al. 2012). The impacts documented ranged from catastrophic loss of whole villages, through destruction of water and sanitation infrastructure, to changes in source water quantity and/or quality (Mosley et al. 2004; White et al. 2007; Keim 2010). Studies have examined aquifer contamination from storm surge in atoll communities (Keim 2010; Bailey & Jenson 2013) and changes in water quality across rainwater tanks, wells and streams (Terry et al. 2001; Horak et al. 2010).

Natural disasters are frequent in PICs and emergency WaSH response is often documented in order to critically assess water and sanitation needs and mitigate the threat of disease in the affected population (Finau et al. 1986; Dengler & Preuss 2003; Choudhary et al. 2012). Examples of intervention include provision of bottled water, rainwater tanks and water treatment methods such as chemical disinfection.

A single large event can remove or damage infrastructure to the degree that entire communities immediately lose access to clean safe drinking water, as was the case for the village of Falelima, Samoa (Martin & Watkins Jr 2010). In that village, it was suggested that rainwater harvesting should be adopted both as a ‘failsafe’ approach following disasters and as a means by which water could be secured for the community pending re-construction (which may take several years).

Development WaSH and Intervention Strategies

A number of studies of 'development WaSH' (WaSH service delivery outside times of disasters) have highlighted reasons for intervention failure. Wohlfahrt and Kukyuwa (1982) evaluated a rural water supply program in PNG and found that 40% of water supply systems failed within one year of installation, largely associated with poor design, construction and maintenance, social conflict and vandalism. More recently, Clarke et al. (2014) reviewed project performance across 27 WaSH interventions in PNG, the Solomon Islands and Vanuatu and found just one project where the outputs were the same or greater than those expected at the end of the initial funding period. This highlights the lack of sustainability of WaSH services in many communities, and the need for local context to be considered as part of intervention development (MacDonald et al. 2012). Indeed, the need for improved understanding of local context and more meaningful engagement with local people is a common thread throughout much of the literature (Mourits & Kumar 1995; Smith Jr 2009; Guerrier et al. 2013). Clarke et al. (2014) pointed out that the technology used in the interventions was not complicated and that low uptake was likely the result of the intervention being incompatible with the local environment and/or community.

In addition to ensuring that interventions are well designed and culturally and environmentally appropriate, behaviour change is required for safe and sustained use of WaSH infrastructure and facilities. Greenwell et al. (2013), Guerrier et al. (2013), and Kuruppu (2009) highlighted the need to address the cognitive or psycho-social barriers that mediate behaviour if WaSH interventions and adaptation are to have sustained benefits. Mourits and Kumar (1995), in the context of rainwater harvesting in Fiji, showed the importance of understanding the cultural setting with respect to supporting individual actions (like establishing household water harvesting schemes), as resources are often shared at the village level. Such cultural issues and the need to understand social structures prior to intervention were cited by many authors as reasons for project failure (see also (Kuruppu 2009; Greenwell et al. 2013; Guerrier et al.

2013). Interventions that do not take into account cultural factors may be inappropriate and ultimately ineffective.

Several studies reported assessments of water quality and contamination across multiple water source types (Mourits & Kumar 1995; Beatty et al. 2004; Horak et al. 2010; Psutka et al. 2013). This is relevant in the context of global WaSH surveys that assess the primary water source of each household, despite the growing evidence that many households use a variety of sources for different uses (MacDonald et al. 2016). Importantly, some studies showed that source water quality, per se, does not necessarily drive acceptance and patterns of use. For example, Horak et al. (2010) showed how rainwater tank water quality was vastly better than water quality in wells and streams in PNG, yet was not the preferred source for drinking and cooking. Households were not using scientific water quality measurements to guide their decision-making and patterns of use, so more work linking perceptions of water safety to measures of water safety would aid our understanding of how PIC communities value and use their water.

Whilst medium-term impacts of WaSH interventions were little studied (Clarke et al. 2014), a handful of studies evaluated the short term impacts of interventions. For example, Vail (2002) examined the family health and farming practices of communities in PNG following interventions. The challenge in that study, as in many others, was that the goals of the project were very broad, 'to improve water, sanitation and farming practices,' and the end-points, such as human health improvements, very difficult to measure and to relate to program. This raised an important problem which is evident in the WaSH literature – are the goals measurable, and if so, when should they be measured, by whom and how?

Resource and capacity constraints, environmental risk and uncertainty, and social conflict influence the success and sustainability of WaSH interventions in the PICs (Hadwen et al. 2015). The need for WaSH services is widely recognised, however, data scarcity challenges informed water management decision-making and the assessment of intervention options (Chan et al. 2010). Bayesian Network models have been applied in Kiribati (Moglia et al. 2012) and the Solomon Islands (Chan et al. 2010) to foster

participatory planning and decision-making for urban water management, integrating diverse expert and local knowledge in the assessment of intervention strategies and identification of causal factors likely to influence intervention outcomes. Participatory approaches have also proven to be effective in gathering information from and fostering constructive relationships between stakeholders, in recognition of local knowledge, competing interests, and systems complexity (Terry & Khatri 2009).

Management and Governance

Here we defined WaSH management and governance as any processes relating to conceptualizing, planning, implementing (including support activities such as capacity building; and ongoing activities such as operation and maintenance), monitoring and evaluating intended to generate water, sanitation or hygiene outcomes. These involved state and non-state actors, and stakeholder participation was a critical aspect of governance. For this review, we included any scale of implementation from local village to national or regional PICs.

Recent studies have employed both frameworks and narrative approaches to evaluate national or regional-scale management and governance arrangements. For example, Keen (2003) used the integrated water management framework to guide a critique of policy, institutional and socio-cultural dimensions of water, sanitation and water resources management in Suva, Fiji. Wutich et al. (2014) concluded that there is a general willingness to engage in 'soft pathway' solutions (water conservation, efficiency and allocations) to water availability problems.

Several articles addressed urban water management directly (Tuhaika Jr 2007; Poustie & Deletic 2014). Tuhaika's evaluation provided an assessment of cultural factors limiting the performance of a state-owned water utility in Solomon Islands to support the case for privatization. Storey and Hunter (2010) stressed that greater effort is needed to manage anthropogenic impacts arising from increasing urbanization and development relative to the effects of climate change.

Several themes emerged from evaluations of management and governance. The first was the importance of considering context, also mentioned in the Emergency WaSH and intervention strategies section. This included the need to harmonize governance and management approaches with local socio-cultural factors (Carden 2003; White et al. 2008; Wutich et al. 2012), the importance of understanding water and resources ownership customs and conflicts (Keen 2003; Storey & Hunter 2010; Wutich et al. 2012), the value of integrating indigenous knowledge and values with best practices (Smith Jr 2008), and the need for locally-appropriate sustainable technologies (South et al. 2004; Smith Jr 2008).

Challenges with institutions and policy are also highlighted, with papers detailing fragmented and uncoordinated governance arrangements (Keen 2003; van der Velde et al. 2007; Kumar 2010), failures in policy and planning implementation (South et al. 2004; Storey & Hunter 2010) and inadequate legislation (Keen 2003; White et al. 2008; Storey & Hunter 2010). Finance was cited as a challenge by several papers, with some describing inadequate financing of WaSH (Carden 2003) and need for cost recovery, water pricing and issues of willingness to pay (Keen 2003; Kumar 2010; Storey & Hunter 2010), as well as insufficient investment in maintenance of facilities (Wohlfahrt & Kukyuwa 1982; Keen 2003).

Various authors described a need for improved stakeholder participation in governance (South et al. 2004; Kumar 2010) and specifically community participation in projects and governance generally (Keen 2003; White et al. 2008; Storey & Hunter 2010). Community awareness and education may have facilitated participation (Keen 2003; South et al. 2004; Smith Jr 2008) and community institutions had a role in supporting this (Schoeffel 1984). Inadequate human resources and capacity development activity (Carden 2003; van der Velde et al. 2007; Storey & Hunter 2010) were challenges, however, several authors claimed that reliance on external support can result in unsustainable outcomes (Smith Jr 2008; Storey & Hunter 2010).

Several authors highlighted the need for effective use of information. Some suggested using it to guide planning and management (Keen 2003; Denton & Sian-Denton 2010; Storey & Hunter 2010), while

others recommended assessing long-term environmental and/or social impacts of new developments in addition to financial impacts (van der Velde et al. 2007; Smith Jr 2008). A final theme for the management and governance papers was the need for catchment-scale planning and management of water resources (Smith Jr 2008; Kumar 2010).

Although there was recognition of many problems in management and governance arrangements, as evidenced by the relatively large number of evaluative publications highlighting these issues, solutions to these problems were less evident in the literature. Ten articles described approaches or tools that managers could use to improve management and governance of WaSH, including a framework to consider the gender outcomes of WaSH programs (Carden 2003), models to integrate various aspects of urban water (Poustie & Deletic 2014), participatory modelling approaches to evaluate likely success or failure of projects (Moglia et al. 2008, 2012) and participatory approaches to support community risk-based water management (Smith Jr 2009; Chan et al. 2010; Hasan et al. 2011). Hoverman et al. (2011) described social learning processes that engage community members in water management and integrate the knowledge of all stakeholders.

In addition to these articles directly addressing management and governance of water, sanitation or hygiene, other published studies provided insights useful to WaSH managers. For example, Repič (2011) studied urban space and social organization within informal urban settlements of PNG through the lens of water access, providing insights into water service delivery in these lesser-studied communities. Tran et al. (2006) described the personal hygiene practices of youth in Vanuatu, Tonga, and Federated States of Micronesia, providing recommendations for managers in the design of hygiene interventions.

DISCUSSION

The first objective of this paper was to review and report the state of research around all aspects of WaSH, encompassing water resource management, water supply, sanitation and hygiene in the PICs

according to the peer-reviewed literature. The overwhelming majority of papers identified in this review were water-focused, followed by sanitation and then hygiene. At first glance, this seems a reasonable bias in a tropical region with high average temperatures, limited area for surface water capture and limited freshwater resources on scattered landmasses surrounded by ocean. However, as highlighted in a number of the studies reviewed here, improper or inadequate sanitation poses a serious contamination threat to an already-limited freshwater supply (Merson et al. 1977; Mosley et al. 2004; Fujita et al. 2014), and increases the vulnerability of a community already relying on a finite water source. Poor hygiene has also been flagged as a leading vector of disease transmission in PICs (Bukenya & Nwokolo 1990; Greenwell et al. 2013), and yet trails in the number of studies performed. In general, the scientific literature provides a good understanding of the water cycle on island atolls, including organic and chemical contamination risks to the freshwater lens, but limited insight into the water cycle on more mountainous islands prone to flooding, such as the Solomon Islands and Fiji, or links between water quality and availability. The number of studies related to the management and governance of WaSH systems, and to a lesser extent those of disaster response, are increasing more rapidly than studies about either public health or the environment, reflecting the research community's awareness of the vulnerability of PICs to an increasingly variable climate.

The second objective was to explore spatiotemporal publication trends in peer-reviewed WaSH research performed in the PICs. Most apparent in this analysis was the high number of publications undertaken in PNG which greatly exceeded all other countries. The most common type of study performed in PNG was of public health, with many focused on the transmission of typhoid or cholera, along with the study of zoonotic diseases, such as brucellosis and leptospirosis. Given that PNG has the largest population in the region with the highest diarrhoeal mortality rate amongst children in PICs, and has only 19% and 40% coverage of improved sanitation and drinking water, respectively (WHO et al. 2016), this may explain why research efforts have been concentrated there. PNG also represents approximately 70% of the regional population. The Solomon Islands, with an estimated 5% of the regional population has the

second lowest rate of improved water and sanitation coverage in the region (UN 2015), but was the focus of only four research articles. Despite the creation of WaSH policy, PICs are limited by an inadequate level of on-the-ground programming and practice. The importance of understanding and incorporating knowledge of local geographies and local traditions underpin the success of WaSH interventions (Smith Jr 2009; Guerrier et al. 2013; Clarke et al. 2014).

With respect to temporal trends, peer-reviewed WaSH publications have increased in number since 1955 with increases in 1990 and again in the early 2000's. Early research focused on public health and environmental issues, which remain prominent, but publication of disaster risk reduction, interventions, and management and governance research has accelerated since 2005. It is reasonable to suggest that international policies, such as the United Nation's MDGs, and the findings of global monitoring efforts, put the PICs in the spotlight, revealing their comparative lack of progress.

The third objective of this review was to identify emergent themes within the peer-reviewed literature and suggest areas in greater need of research. The literature suggests that without enough water for handwashing and personal hygiene there is a greater risk of exposure to enteric pathogens (Bukenya & Nwokolo 1990; Greenwell et al. 2013; Prüss- Ustün et al. 2014), and inadequate animal husbandry practices increase this risk (Berlioz-Arthaud et al. 2007; Guerrier et al. 2013; Thompson et al. 2014). The literature also implicitly characterizes some of the extreme challenges associated with WaSH service delivery in the region, such as how droughts and water shortages impact the freshwater lenses of low-lying coral atolls (Ghassemi et al. 1990; Griggs & Peterson 1993; Koda et al. 2013), as well as some understanding of the potentially-worsening conditions caused by climate change (Rapaport 1990; Roy & Connell 1991; White et al. 2007). WaSH interventions are intended to curb this risk using different mechanisms and barriers to exclude pathogens from food and drinking water, but many have thus far been unsuccessful or unsustainable (Wohlfahrt & Kukyuwa 1982; Clarke et al. 2014). Lastly, a shortage of both human and financial resources, along with uncoordinated planning and implementation from

different levels of local government have been cited as reasons for failed attempts at the implementation of WaSH policy and legislation (Keen 2003; South et al. 2004; van der Velde et al. 2007).

Knowledge gaps

Several knowledge gaps emerged from our review of WaSH research in PICs. Despite nearly unanimous agreement that personal and food hygiene play an important role in disease transmission, the impact of hygiene interventions and specific cultural factors on population health was poorly described in the peer-reviewed literature from the PICs. The unique waterscapes of PICs means that hygiene and handwashing practices are tangibly different from other countries and that general knowledge on these subjects likely does not transfer. Additional research would facilitate better programme design and provide a more complete understanding of the barriers to handwashing in PICs. With respect to environmental studies, which are closely related to public health, more sanitation technologies and behavioural interventions are needed to reduce the proportion of PIC populations who practice open defecation and use bottomless 'septic tanks' that risk contaminating groundwater resources.

The disaster response literature lacked a thorough assessment of the short, medium and long term consequences of emergency WaSH. Dengler and Preuss (2003) provided a useful framework for understanding the four stages of disaster recovery (response, relief, recovery and reduction of vulnerability), which enabled us to highlight where the bulk of the work has occurred and where the greatest knowledge and resource gaps remain. Seventy-five percent of the reviewed papers focused on disaster response and recovery in the immediate aftermath of a particular event. As a result, the elements of reconstruction and rehabilitation and reducing the impacts of future disasters were largely missing from the existing literature.

While many management and governance initiatives produce evaluations, they infrequently adhere to rigorous standards, nor do they prioritise sharing lessons in peer-reviewed literature. Acknowledging this, we identify gaps around management and governance. Indeed, the available literature revealed the need

for evidence guided management strategies that prioritize human health and well-being, while concurrently protecting and preserving the natural resources they rely upon for safe drinking water. This could include the assessment of different 'systems' approaches to WaSH planning, which involve local stakeholders as active and equal participants in the development process, and that harmonize the protection of freshwater resources from 'ridge to reef' with an appreciation for the local socio-cultural context.

CONCLUSION

As we usher in a new generation of development goals, it is timely to reflect on WaSH performance against the MDG target, and pay due diligence to why PICs lagged behind other regions in 2015. In order for PICs to meet the SDGs, we need a better understanding of the immediate challenges, such as extreme environmental conditions, urbanization, climate change, and how to implement solutions in small and remote communities that are often both difficult and expensive to reach. It is clear from this systematic review of peer-reviewed WaSH literature on PICs that better coordinated governance along with adequate financing and maintenance of facilities has the power to accelerate progress towards achieving SDG Target 6.1, universal and equitable access to safe and affordable drinking water for all by 2030. Intervention technologies and behavioural strategies offer decentralized solutions to drinking water shortages, but may also represent opportunities in PICs towards achieving Target 6.2, adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations. With greater consideration of culturally and environmentally appropriate sanitation technologies in PICs that guard against the contamination of freshwater resources, thoughtful intervention strategies could also accelerate regional achievement of SDG Target 6.3, improve water quality by reducing pollution… halving the proportion of untreated wastewater […]. In PICs, the protection and optimization of multiple water resources is critical in water-

use efficiency and building resilience to climate threats. Globally there is growing awareness of the need for sustainable freshwater withdrawals and this is particularly important on island atolls with limited resources. Beyond this realization, achieving the SDGs in PICs will require greater environmental, social and cultural contextualization to understand the water management strategies used in PIC societies. In the context of Goal 6 of the SDGs, this will require a more holistic view of WaSH research and development needs to align the efforts made towards individual targets. Simultaneously, these integrated approaches will aid in the recalibration of research priorities that aim to inform greater WaSH coverage while simultaneously protecting the health of local ecosystems and natural resources from which PIC communities source their water.

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Figure 1

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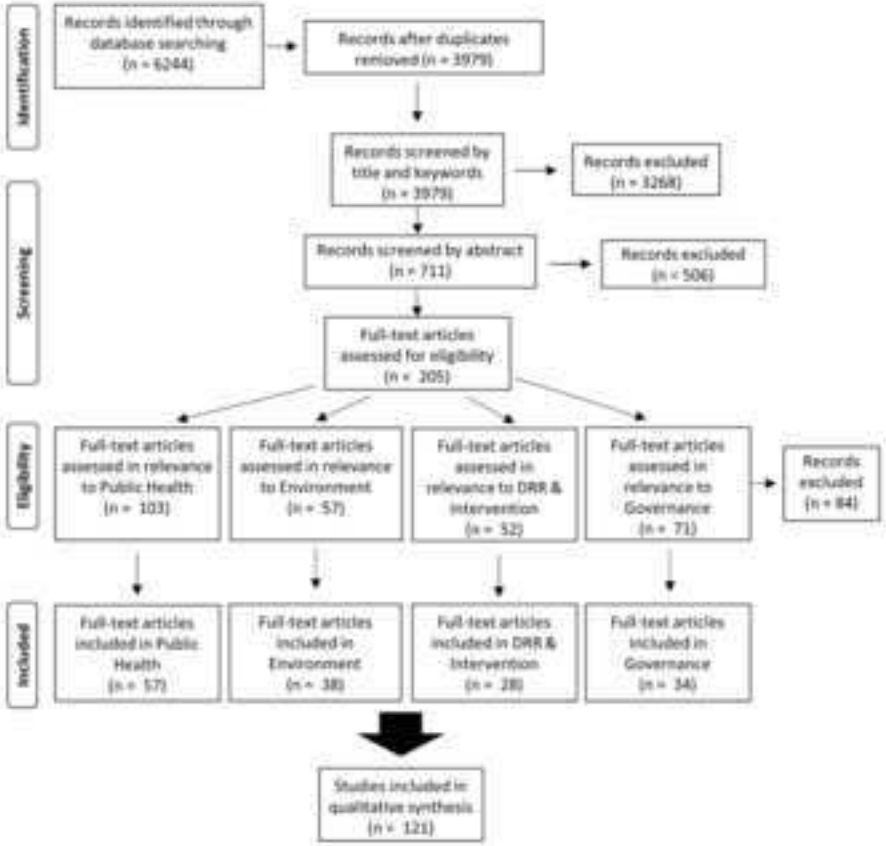

Figure 2

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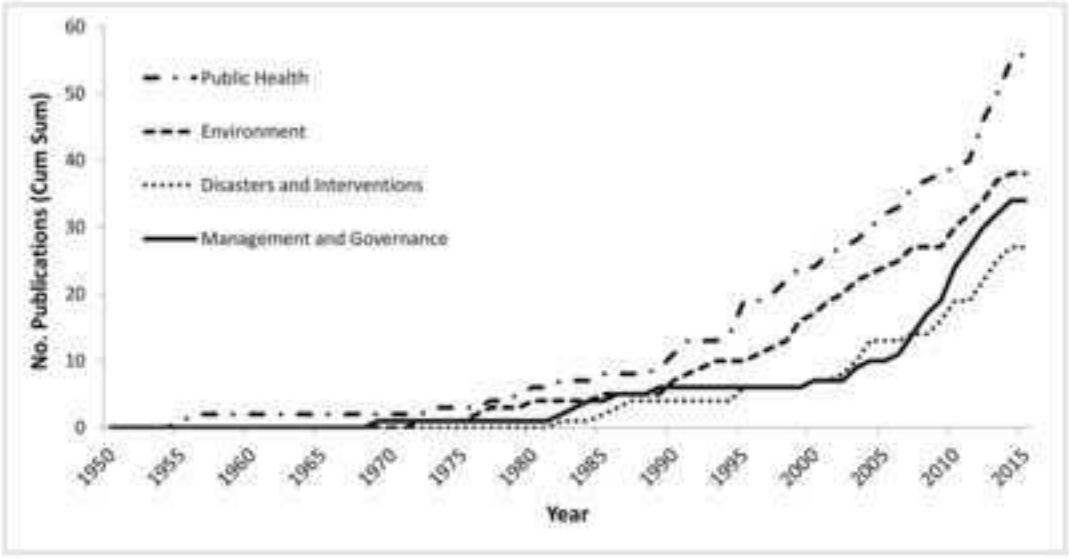

Figure 3

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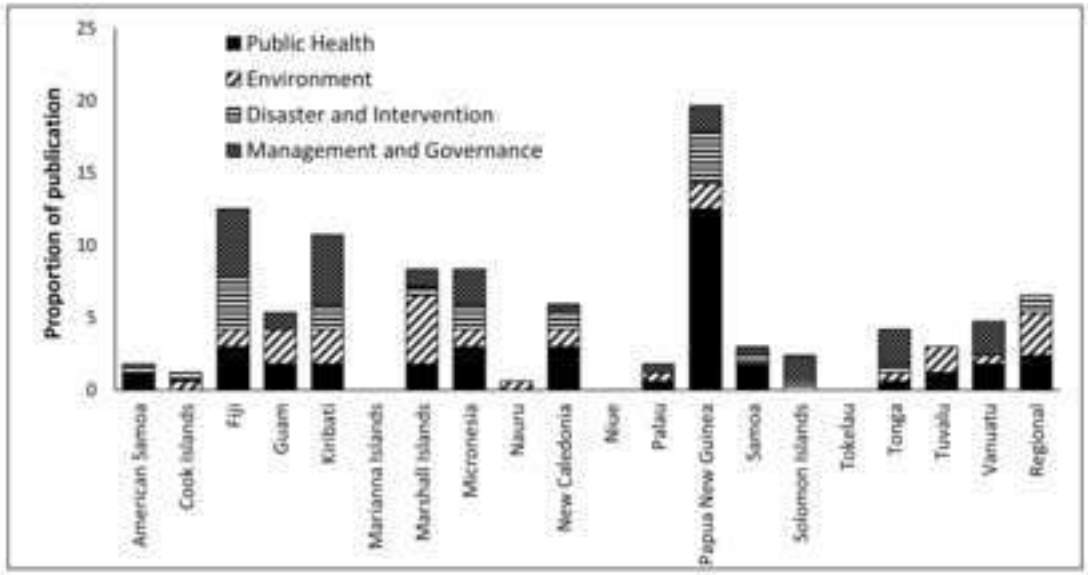

Table S1. Term Combinations for Database Searches of Peer-reviewed Water, Sanitation and Hygiene Research in Pacific Island Countries.

GEOGRAPHY	**and**	**WaSH**	**and**	**HEALTH**
American Samoa		Water		Diarrhoea/Diarrhea[Ŧ]
Cook Islands		Drinking water		E.coli/Escherichia[Ŧ]
Fiji		Sanitation		Coliforms
Guam		Defecate		Helminths
Kiribati		Toilet		Trachoma
Marianna Islands		Freshwater		
Marshall Islands		Groundwater		
Micronesia		Hygiene		
Nauru				
New Caledonia				
Niue				
Palau				
Papua New Guinea				
Samoa				
Solomon Islands				
Tokelau				
Tonga				
Tuvalu				
Vanuatu				
Pacific Island Countries				

Ŧ Multiple searches were performed using variations in spelling.