A Case Study Assessing Potential Enteric Zoonotic Pathogen Risks to Beachgoers at a Perth Metropolitan Beach.

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ABSTRACT

Beaches in Australian coastal locations provide popular, inexpensive, and accessible natural resources in which members of the community can engage in a variety of aquatic and land-based leisure or recreational pursuits. While many positive social and health benefits can be attributed to participating in beachgoing activities, potential negative health outcomes from exposure to biological pathogens introduced through point source processes can also occur. While advancement in wastewater treatment system technologies in developed nations have reduced this health burden somewhat, other contributing sources including via diffuse processes continue to remain largely unexplored in relation to human health impact within the academic literature.

This study examines diffuse contamination from domestic animal sources at recreational marine environments and the potential gastro-intestinal health risks through incidental ingestion exposure for adult beachgoers in Australia. This is achieved through providing a comprehensive overview of current national management guidelines and practices, conducting a systematic literature review and critique of research undertaken within the field. A case study will also be used in assessing adult GI health risks associated with diffuse source contamination exposure, while engaging in recreational beach activities.

Guided by knowledge gaps in the field identified within the systematic literature review, the primary research area of investigation was formulated in addressing the question, ‘Do recreational beach exposures which are also promoted for use by domestic animals (dogs and horses) pose an increased public health risk to beachgoers? A Case Study Assessing Enteric Zoonotic Pathogen Risks at a Perth Metropolitan Beach’.

This topic attempts to address potential human health hazards observed within metropolitan beach locations within Western Australia. A focus is also placed on sources of enteric pathogen contamination introduced to both marine waters and beach sand by domestic animals (dogs and

horses), that are permitted access with their owners to beach sites which are also used by families for recreational purposes. This research topic explores areas of investigation which have achieved limited attention previously within the published literature therefore, current findings contribute to unique knowledge insights into GI health outcomes associated with diffuse source microbial contamination in marine settings.

Findings from this study indicate a possible marginal increase in human gastro-intestinal health risk from exposure to zoonotic enteric bacterial pathogens compared with similar protozoan pathogens. Measured against microbial parameters set within current national recreational water guidelines, *Campylobacter* present in domestic canine faecal contamination of beach sand presented the greatest measure of health risk to adult beachgoers due to a single exposure. *Salmonella* and protozoan pathogens including *Cryptosporidium* and *Giardia* were measured at acceptable levels as defined within the national recreational water guidelines for both dog and horse faecal contamination in both sand and water environments. Caution with the extrapolation of findings from this case study across other marine environments should be considered due to a number of heterogenous factors both considered and excluded within this desktop-based research.

This research topic is intended as a preliminary exploration into potential human health risks upon exposure to enteric pathogens from domestic animals introduced into a recreational marine environment. It is anticipated that findings from this study will contribute towards the ongoing evolution of knowledge, practice, and policy development in supporting public health measures aligned with recreational marine environments nationally and abroad.

DECLARATION

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Signed........... 

Date. 17/10/2022

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PART 1 - NATURAL RECREATIONAL WATER QUALITY AND ILL HEALTH IN AUSTRALIA

1.0 Introduction

Natural aquatic recreational environments are acknowledged as important resources in supporting the health and sustainability of aligned communities and individuals. Natural recreational waterbodies including coastal, estuarine and freshwater environments consist of complex ecosystems that sustain a functional symbiotic relationship between a variety of independent organisms (WHO, 2021). Ensuring the natural and introduced hazards associated with these waterways are suitably managed in support and maintenance of protective public health practices remains a challenging yet important requirement for managing agencies.

The following work provides a comprehensive investigation into the many facets of water quality, relating to natural recreational waterbodies in Australia and the impact this has upon the health outcomes of those exposed. While it is acknowledged that many different types of hazards may be associated with these aquatic environments, a focus on microbiological contaminants will remain the focus of this paper.

This thesis will be structured using three main sections, the first will introduce the reader to natural recreational water system management in Australia. A brief summary of the origins of recreational water management systems from an international perspective will be conducted in setting the foundation to explore the current systems applied in Australia.

A systematic literature review will comprise the second section, with a focus on developing a comprehensive understanding of the totality of national recreational water management systems. A review and critique of the published literature will be used to formulate a novel and independent research project, which will contribute towards advancing the knowledge and practices of natural recreational waterways management into the future.

A case study involving a risk assessment formulated from knowledge attained during the previous systematic literature review will constitute the final section of this work. This will address an important human health issue within the context of enteric pathogen contamination from domestic animal sources at recreational marine environments. This topic has maintained very limited attention within an Australian context to date and studies within the published literature are also under-represented. It is envisaged that findings from this current risk assessment will aid in contributing towards a new direction of public health enquiry for marine recreational settings.

2.0 Background

Coastal and inland waterbodies offer natural settings for year-round leisure, sport and recreational opportunities for a diverse range of population groups with the community. The array of benefits these environments have across the community can be seen through the realms of 'economic, social, and cultural' (Weiskerger, Brandão, Ahmed et al., 2019) spheres offering diverse value as both a community asset and a resource. A variety of user groups including specialist groups, local residents and seasonal or sporadic users also experience the health and wellbeing benefits aligned with their selected form of engagement (Petterson, Li, & Ashbolt, 2021; Weiskerger, Brandão, Ahmed et al., 2019). Natural aquatic recreational environments are acknowledged as important resources in supporting both individual health benefits but may also support community cohesion and identity which potentially contribute to supporting positive health outcomes for the community.

While it is acknowledged there are many associated benefits of natural recreational waterbodies to the community there also exist many physical, chemical and biological hazards which can have a negative impact on human health. Direct or incidental exposure to waterborne pathogens, toxins and irritants can produce a range of symptoms from short-term self-limiting health ailments through to potentially serious or life threatening conditions if the water is polluted or identified as unsafe (Mannocci, La Torre, Spagnoli et al., 2016). A wealth of supporting evidence demonstrate that higher illness rates of swimmers compared to non-swimmers specifically for gastrointestinal (GI), and acute febrile respiratory illness (AFRI) exist however, similar findings have also been observed to impact eye, ear and skin health (Fleisher, Fleming, Solo-Gabriele et al., 2010; Mannocci, La Torre, Spagnoli et al., 2016; Sinclair, Jones, & Gerba, 2009; Wu, Wang, Zhang et al., 2020). Developing a greater understanding of biological hazards associated with recreational water exposure can assist in also building a greater understanding of the associated health risks.

The global burden of mortality and morbidity cases attributable to human wastewater exposure in a recreational setting is extensive and far-reaching. The World Health Organization (WHO, cited in Henry, Schang, Kolotelo et al., 2016) estimates that approximately 2.5 million fatalities are linked to contact with contaminated recreational water sources annually worldwide. Napier, Haugland, Poole et al. (2017) report that due to swimming in polluted waters approximately 170 million enteric and respiratory illnesses are caused annually worldwide. While Abdelzaher, Wright, Ortega et al. (2011) also highlight that approximately 120 million cases of GI disease and more than 50 million cases of RI are associated with recreational exposure to coastal waters that are polluted with human wastewaters. Within an Australian context, Ryan, Lawler, and Reid (2017) estimate at total of 15.9 million GI cases (from all sources) each year which translates to over a one billion dollar economic cost due to medical expenses and absenteeism annually.

An acknowledged understanding of the negative health impacts of exposure to faecal pathogens during aquatic recreational participation has led health authorities in most developed nations to implement community wide protective health measures. These features are typically demonstrated through agencies setting acceptable or recommended water quality parameters which are monitored and reviewed through a pre-determined sampling period.

2.1 International Recreational Water Quality

Historically an increased interest in microbial quality and human health impacts of recreational water exposure appeared in the early twentieth century with the American Public Health Association's Committee on Bathing Beaches (Wymer, Wade, & Dufour, 2013). However , it wasn't until the 1950's that epidemiological enquiry in both the United States and United Kingdom began to explore a possible link between recreational water exposure contaminated with human wastewater and an associated human health risk (Abdelzaher, Wright, Ortega et al., 2011; Fewtrell & Kay, 2015; Leonard, Singer, Ukoumunne et al., 2018; Prüss, 1998; WHO, 2021; Yau, Wade, de Wilde et al., 2009). Much of this early research focused on exposure-response relationships primarily involving bathing in marine waters with known human wastewater contamination and health symptoms associated with 'gastrointestinal, respiratory, ear, eye, throat, skin or wound infection (Fewtrell & Kay, 2015; Sinclair, Jones, & Gerba, 2009).

The foundation of this initial research focused around randomised studies on health impacts of human enteric bacterial contamination of recreational marine waters in the United Kingdom. Subsequent research findings by Fleisher, Kay, Salmon et al. (1996) and Kay, Fleisher, Salmon et al. (1994) had formulated a clear relationship between enteric bacteria, primarily enterococci and *E. coli* to GI illness. These findings, in addition to international outbreak reporting data have demonstrated a causative relationship between marine and freshwater bathing and an increased incidence of various health ailments in swimmers compared to those of non-swimmers (Prüss, 1998).

In response to these findings, the WHO adopted enteric bacteria as the primary indicator markers in setting threshold criterion by which human health risk is monitored and accessed in recreational waterbodies. In essence, recreational water measured against this criterion is expressed as the maximum density level of the indicator pathogen which is seen to represent an acceptable level of health risk upon exposure for bathers. Initial threshold levels for example, were set for GI illness

(32 CFU per 100 mL $^{-1}$) and AFRI (60 CFU per 100 mL $^{-1}$) (Ashbolt & Bruno, 2003; Prüss, 1998) which allowed health and managing agencies a quantifiable reference point in which to gauge potential health risk. The implicit foundation of the WHO approach therefore is the notion that health risk is seen as unacceptable in cases where measures exceed a pre-determined threshold level.

The 'Annapolis Protocol' (1998) a WHO and USEPA initiative, in support of a proceeding iteration the 'Farnham Protocol' (2003) led by WHO, set about implementing a new direction in recreational water quality management. Based largely on a health risk framework, this model looks to move beyond traditional retrospective numerical compliance strategies and into real-time risk management and public health protection measures targeting site-specific aquatic hazards (WHO, 2003). This approach utilises a risk assessment perspective, which is conducted through the completion of a sanitary inspection (SI) of the site in addition to microbial water quality sampling and assessment. From this perspective recreational water assessment was based on a cumulative analysis of both a microbial assessment and the completion of a SI. This two-phased approach in recreational water management was adopted by WHO and implemented into the international Guidelines for Safe Recreational Water Environments, Volume 1- Coastal and Fresh Waters (2003).

Many developed nations of the western world, including Member States of the European Union, the United Kingdom (UK) (EU Bathing Water Directive [BWD, (EU 2006/7/EC)], the United States (Recreational Water Quality Criteria [RWQC, 2012]), Canada (Guidelines for Canadian Recreational Water Quality [RWQGs, 2012]) and New Zealand (New Zealand Microbiological Water Quality Guidelines for Marine and Freshwater Recreational Areas (NZ Guidelines) (MfE, 2003) continue to apply national frameworks in regulating the microbial contamination of recreational waters based on varying degrees from this pioneering document.

2.2 Australian Recreational Water Quality Guidelines

The overarching framework used in setting Australian recreational water standards is derived from the National Health and Medical Research Council's (NHMRC) 'Guidelines for Managing Risk in Recreational Water'. The NHMRC, (2008) has developed these guidelines for the purpose of hazard management and reducing health risks specific to recreational water quality practice in Australia. These guidelines seek to provide a national risk-based approach, with the aim of protecting human health while engaging in the recreational use of marine, estuarine and fresh waters environments. The NHMRC, (2008) guidelines are based directly on the WHO Guidelines for Safe Recreational Water Environments (WHO, 2003) which aims to incorporate international best practice into the context of guiding recreational water quality within a localised setting. The Australian Guidelines however do not have regulatory status, rather they aim to provide guidance for governing agencies in the management of local recreational waterbodies.

2.2.1 Enteric Pathogens

The Australian recreational water quality guidelines provide a framework which outlines the recommended levels of faecal indicator bacteria (FIB) in waterbodies intended for human recreational purposes (Russo, Eftim, Goldstone et al., 2020). The WHO recommends, based on a lack of evidence supporting a dose-response relationship, that enterococci rather than *E. coli* be used as the microbial indicator for marine waters (WHO, 2021) Currently there exists some conjecture within the associated academic literature regarding which markers identify as the most reliable predictors of faecal contamination in recreational waters and if these markers hold the same validity across both marine and freshwater environments.

For microbial quality, current Australian recreational water guidelines recommend that recreational water quality should be assessed using both a large (minimum of 100) number of enterococci sample counts (representing the 95^{th} percentile) in conjunction with information provided through current sanitary surveys. The 95th percentile method has been adopted as it provides site specific application offers users simplicity in use and application over alternative methods such as the geometric mean (WHO, 2021). However, greater statistical uncertainty (Patat, Ricci, Comino et al., 2015), and the assessment process getting lost in the daily site application (Ashbolt, Schoen, Soller et al., 2010) are two of the main deterrents of the system.

The overall health risk assigned for a specific recreational waterbody is determined through the categorisation of combined results emanating from both a sanitary inspection and a microbial assessment. This risk assessment approach enables decision making to be undertaken from the inclusion of various information sources and removing the reliance on a single deterministic numerical threshold (NHMRC, 2008).

2.2.2 Microbial Assessment Category (MAC)

Four Microbial Assessment Categories (A to D) exist, which are derived from the 95th percentile of an enterococci dataset consisting of a minimum 100 data points taken from a specific recreational aquatic site. Previous epidemiological evidence from comparable environments has also been aligned with each of the categories and is used to identify varying levels of illness risk. Table 1 provides a representation of the recreational exposure for intestinal enterococci (CFU/per 100 mL) against the corresponding illness risk for GI and AFRI, suggesting as exposure increases so does illness risk.

Table 2. Percentile Values for Determining Microbial Water-Quality Assessment Categories

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Source: (NHMRC, 2008, p. 72).

As shown above, enterococci counts are partitioned into four MAC's, A, B, C and D with each category representing a varying degree of illness risk based on the level of exposure.
Table 1 illustrates for example that enterococci counts between 40-200 CFU mL are aligned to Category B, this equates with a water contact exposure risk for GI illness estimated at between 5-10% and 1.9-3.9% for AFRI. It is also seen that as the exposure increases so does the expected health risk.

2.2.3 Sanitary Inspection (SI) Category

The sanitary inspection uses a qualitative risk assessment approach by assigning a faecal pollution source into one of five sanitary inspection categories which range from very low to very high as it relates to faecal susceptibility from various sources. This qualitative approach is presented as a screening approach for the purpose of determining a sanitary inspection category as a component of the risk determination process. A sound SI is used to form the basis in the design and implementation of an appropriate water sampling program in addition to assisting in the holistic interpretation of water quality exposure risk (Abbott, Lugg, Devine et al., 2011). As the SI assesses the likelihood of contamination from faecal bacteria it is advantageous that some level of correlation is evident with the bacterial results generated from water sampling.

Table 3. Classification Matrix for Faecal Pollution of Recreational Water Environments

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Source: (NHMRC, 2008, p. 85)

In determining an overall level of health risk, the results from the MAC are then combined with results from the CI to form the matrix provided in Table 2. Aquatic recreational sites are subsequently graded on a five-level classification system from 'Very good' to 'Very poor', which consequently relates to potential health risks associated with primary contact exposure. In instances where findings from the SI and microbial assessment are at odds, the NHMRC guidelines recommend a “Follow up” investigation with both components.

2.2.4 Cyanobacteria and Algae

Australian recreational water guidelines relating to cyanobacteria and algae exposure apply a separate health risk criterion based on fresh water or coastal and estuarine waterbodies. In relation to exposure of cyanobacteria in fresh recreational waterbodies is based on a two-tiered system which forgo the lowest tier of the WHO three tier system. Level 1 of the NHMRC guideline is based on microcystin toxin exposure risk through ingestion (NHMRC, 2008). Level 2 of the guidelines focus on protective feature assigned high levels of cyanobacteria, measured through cell count and biovolumes, of non-toxic cyanobacteria (NHMRC, 2008).

In assessing cyanobacterial and algal water quality, a combined measure including the susceptibility of the waterbody to algal contamination in addition with historical monitoring assessment results determine an overall level of classification (NHMRC, 2008). Within this matrix, five possible classification systems may be applied ranging from ‘Very good’, ‘Good’, ‘Fair’, ‘Poor’ and ‘Further assessment required’. Refer to Table 3. It is stated within the guidelines that assessments categorised as ‘Very good’ typically comply with the guidelines, while those found to be “Very Poor’ generally do not pass the guidelines.

Table 4. Cyanobacteria and Algae in Freshwater Suitability for Recreation Matrix

Figure removed due to copyright restriction

Source: (NHMRC, 2008, p. 109)

The NHMRC guidelines used in the assessment of cyanobacteria and algae in marine and estuarine waters differ from the criteria used in the assessment of freshwater. Refer to Table 4 for cyanobacterial and algal water quality classifications for coastal and estuarine waters. It is stated within the guidelines that assessments categorised as ‘Very good’ typically comply with the guidelines, while those found to be “Very Poor’ generally do not pass the guidelines. Further monitoring is recommended by water management authorities when waterbodies are assessed as either, ‘Good’, ‘Fair’, or ‘Poor’.

Table 5. Cyanobacteria and Algae in Coastal and Estuarine Waters, Suitability for Recreation Health Risk Matrix.

Figure removed due to copyright restriction

Source: (NHMRC, 2008, p. 128)

3.0 Conclusion

Recreational water quality specific to natural waterbodies is typically monitored by most western nations worldwide using FIB levels as an indicator for human health risk. International agencies including the World Health Organization recommend the use of *E. coli* in freshwater and intestinal enterococci in marine waters as indicator markers for hazard monitoring. While enteric bacterial pathogens are the primary measure, it is also used as a proxy indicator in assessing other potentially harmful waterborne viruses, bacteria and protozoa serving therefore as an overall public health measure.

The National Health and Medical Research Council (NHMRC) in 2008 published Guidelines for Managing Risks in Recreational Water. These guidelines were developed as a reference document aimed as providing an information resource to public, government agencies and other key industry stakeholders in guiding recreational water management practices. They apply to all natural water bodies (coastal, estuarine and fresh) that are used by the public for recreation. Accepted health targets are prescribed for both microbial and cyanobacterial agents are applied at a national management level and implemented through a two phased system of water sampling and a sanitary inspection which are conducted at a local management level.

PART 2 - A SYSTEMATIC LITERATURE REVIEW

4.0 Aim

The overarching aim of this research project was to complete a comprehensive review of available literature relating to recreational water quality, human exposure and public health outcomes specifically within an Australian context. It is envisaged that findings drawn from this study will highlight current knowledge gaps within the field of recreational water quality nationally and further development of evidence-based policy and practice in the protection of public health can ensue. This information will also be used in guiding a risk assessment analysis aimed at addressing an identified biological recreational water hazard which is a potential population health risk.

The purpose of this systematic literature review was to gather and investigate the relevant evidence in understanding;

1. What is known about the human health impacts of microbiological contamination of natural recreational waterbodies on users in Australia?
2. What are the associated human health risks, who is impacted and how are these monitored, reported, and managed in Australia?
3. What is the current status of research, what is known and identify any gaps in the literature regarding recreational water quality and public health in Australia?

5.0 Objectives

The primary objectives designed to meet the needs of this research project we to:

(1) Investigate and assess the published literature relating to the illness risks associated with the various types of aquatic recreational activities which involve varying degrees of water contact.

(2) Strengthen evidence-based practices relating to the application, monitoring and management of recreational water quality in Australia.

(3) Explore non-point source biological contamination of pet friendly beaches and assess associated risks in determining a deeper understanding of potential public health impacts.

(4) Identify patterns, trends or gaps in the research literature which could be used to positively influence future directions in recreational water quality standards for natural waterbodies in Australia?

(5) Revise marine pathogen health assessment practice to be holistic and inclusive of an ecological health approach, incorporating beach sand and water analysis in better servicing the health needs of beachgoers.

6.0 Methods

A methodological process was formulated in order to implement a structured search strategy for this systematic literature review. The process used in conducting this systematic literature review was performed under the requirements outlined within the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. This format provides a universally acknowledged approach in sourcing and presenting evidence-based knowledge, which is methodical, reproducible, and transparent.

6.1 Literature Search Strategy

There were three primary search strategies used in gathering appropriate papers including, electronic database searches, grey literature searching and scanning the reference lists of selected papers.

The literature search was conducted using the SCOPUS and Web of Science databases. Keywords were generated from an initial scoping search conducted using these search engines in review of Australian and International literature used to guide practice on recreational water risk and public health policy (WHO, 2003). Boolean operators (OR, AND, AND NOT) were also used to strengthen and refine the search process and minimise the identification of articles outside the realms intended for this systematic review. A selection of keywords was then chosen and applied to construct the search strategy identified in Figure 1.

Figure 1. Complete Search Strategy and All Key Words Used to Identifying Relevant Literature

Search Terms Employed to Identify Relevant Literature
"recreational water*" OR swimming OR lake* OR river* OR coast* OR beach* OR marine* OR estuary* OR reservoir* OR dam* OR weir* OR creek* OR stream* AND "disease*" OR "infectious disease*" OR illness OR contamina* OR outbreak* OR infect* OR "water borne" OR "waterborne" AND "Australia" AND NOT fish* AND NOT "animal disease*" AND NOT "ross river virus" AND NOT "swimming pool*"

Note- * is a truncation symbol used here to retrieve search terms with a common root meaning.

Filters were also applied within the search strategy to eliminate results relating to heavy metal, metals, animal or animals. This aided in providing further precision into the search process with the aim of eliciting papers reflective of the desired field of interest.

When there was an overlap of identified articles between SCOPUS and Web of Science databases, all duplicates were noted and subsequently removed.

Searches were limited to peer reviewed, conference papers and reports with a sole focus on Australian studies. In order to generate a comprehensive exposure to the available literature there were no date limitations placed on the searches. The aim of this approach was to ensure all documented studies focusing on health outcomes measured against recreational exposure to natural waterbodies in Australia were captured.

A grey literature search was also conducted through the web-based search engine Google scholar [www.google.com]. This was conducted to further explore published and unpublished material which could have been missed previously. However, no further papers were sourced using this format which met the stated inclusion/exclusion criteria.

A reference list review, using a ‘snow-balling’ technique, was also conducted on articles selected for the primary screening process for any article which may have been missed during the initial database searches. Again, no additional resources were identified using this technique which met the specified search criteria.

6.2 Inclusion and Exclusion Criteria

The inclusion and exclusion criteria was broadly structured around the key components of the PECOS model which Morgan, Whaley, Thayer et al. (2018) describe as being more supportive of an environmental health approach rather than a PICO or health intervention context. The PECOS format is summarised as follows. (Refer to Table 2 which provides a detailed outline of the inclusion and exclusion criteria expressed within the PECO format).

The study population (P) of interest was defined as Australians engaging in aquatic recreational pursuits. There were no restrictions placed on age or gender. Studies exclusively exploring international populations or included samples within a study with more than 50% derived from outside of Australia were excluded. Exposure (E) to natural recreational water bodies including both marine (salt water) and fresh waters were included. Artificially constructed recreational lagoons and dams were also included. Studies involving artificial chemical disinfection processes of waterbodies such as swimming pools and spas were excluded. All forms of primary and secondary water contact as defined by NHMRC, (2008) within a recreational context were included. All occupational, drinking water or indirect contaminant exposure through aquatic food sources such as fish, oysters or molluscs were excluded from the review. Studies relating to heavy metals, industrial and domestic poisons or toxins were also excluded. Studies had to include a minimum of one numeric water quality measure specific to a microbiological agent to be eligible for consideration. Those papers presenting findings on the modelling, robustness, and accuracy of qualitative microbial risk assessments (QMRA) only, were excluded. Studies presenting anecdotical evidence of recreational water quality were also excluded. Comparator (C) groups assigned within individual studies were also an important requirement for inclusion. Studies that compare variables including polluted verses unpolluted recreational waters, dose-related exposures to contaminants and exposed verses non-exposed will be considered for inclusion. Those study designs such as case studies, case reports or papers which provided commentary or summarised recorded outbreaks were excluded. Outcomes (O) or symptoms relating to human health exposure to pathogens contained within natural recreational waterbodies expressed through physician or self-reported means was also required for inclusion. Any study relating to the health of flora or fauna within the greater aquatic ecosystem was excluded. Study types (S) included those maintaining formally recognised scientific based research methodologies published in the English language.

Table 6. The PECOS criteria used in the screening process including application and rationale descriptions for each criterion.

PECO	Selection Criteria	Application	Rationale
P	1. The study has been conducted using Australian participants within the nation of Australia	Exclude studies conducted in countries other than Australia. Studies incorporating sample groups from outside of Australia which constitute greater than 50% of the total study sample group will also be excluded.	This systematic review focuses on exploring links between recreating in natural water bodies and the associated risk of adverse health outcomes in Australia. Studies conducted outside of Australia may have limited transferability of factors including health outcomes.
E	2. The study explores exposure to natural (untreated) recreational waterbodies only	Studies were eliminated if they focused on swimming pools, spas, and hot tubs.	Natural (freshwater and marine water), untreated recreational waters are the primary focus of this systematic literature review.
	3. The study must examine recreational exposure to natural waterbodies	Studies are eliminated if investigating health outcomes relating to occupational, competitive sporting, or domestic exposure to natural waters.	The study focus is on recreational exposure including primary or secondary contact, domestic and occupational exposure assume different characteristics and are excluded.
	4. Study focuses health outcomes for waterborne pathogens.	Excludes studies examining infections requiring a vector or intermediate host, outside of those identified as waterborne.	Only waterborne pathogenic infections including those requiring an intermediate host are considered.
C	5. A comparator group should also be incorporated into the study in measuring health outcomes.	Exclude study designs, and summaries of outbreaks where a comparator group has not been identified. Comparator groups considered for inclusion may include those identified as non-swimmers, those unexposed to contaminated water-bodies or those with limited or significantly reduced exposure levels.	In exploring potential illness inclusion of a comparator group allowing for understanding of direction and magnitude of health outcome.

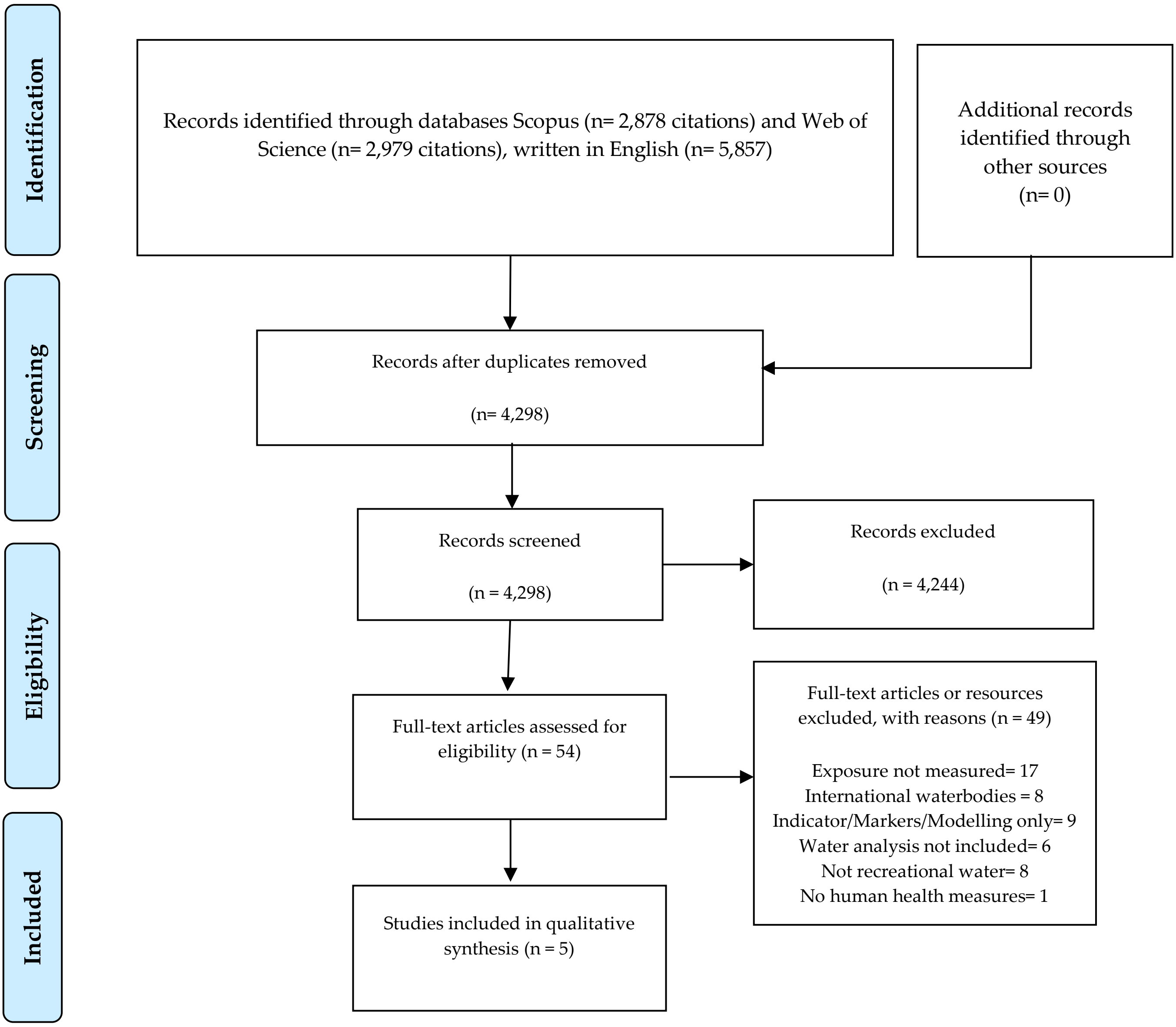
O	6. Only health outcomes in humans are measured in the study.	Studies are excluded if they model, predict or review health outcomes 0r examine health outcomes in non-human cases. The study should include clinically-based diagnosis of infections in addition with self-reported symptoms and health outcomes.	The focus population is limited to humans, and the illness risk for recreators within natural recreational water bodies.
	7. The study examines micro-biological agents and the associated health impacts from exposure.	Studies focusing on non-biological hazards including heavy metals poisons, drowning, and human injuries caused by aquatic fauna are excluded.	The focus is directed towards microbial contaminants including those within human wastewater and the associated public health impacts.
S	8. The study is presented in the English language	Studies published in a language other than English are excluded.	Unable to have documents translated into English due to time and financial constraints.
	9. The study must consist of a recognised scientific research methodology.	Exclude reviews, incident reports, letters, editorials.	High quality, reproducible, sound and accurate research systems that are peer reviewed are considered.

(Adapted from King, Exley, Winpenny et al. (2015) & Leonard, Singer, Ukoumunne et al. (2018)).

7.0 Results

The PRISMA flow diagram (Moher, Liberati, Tetzlaff et al., 2009) (depicted in Fig. 2) is representative of the selection and identification process of articles for this systematic review. A total of 5,857 articles were earmarked as potentially meeting the inclusion criteria, with 2,878 identified within SCOPUS and 2,979 from the Web of Science electronic databases. All corresponding articles were stored on EndNote referencing manager X6, where duplicates were removed, resulting in a total of 4,298 articles. The primary screening stage involved a two-phase process which included a simple title review reducing the overall number of potentially suitable articles to 309. The second step involved abstract screening which excluded another 255 articles, leaving 54 articles which were consequently chosen for full text review. After a review against the defined selection criteria a further 49 articles were excluded. A full list of the 54 review articles is presented as Appendix 2, supported with reasoning for subsequent exclusion. At the conclusion of the screening processes a total of 5 articles were retained for inclusion within this systematic review. A summary of selected articles is presented in Table 6.

Figure 2. PRISMA Diagram of Literature Search



7.1 Overview/ Description of the Selected Articles

7.1.1 Location

All five studies selected as part of this systematic review included participants recruited from Australian natural recreational water settings, as per the requirements outlined within the inclusion and exclusion criteria. The study by Stewart, Webb, Schluter et al. (2006) while focusing on Australian cases also included a sample population from Florida (USA). This article was included as a vast majority (84%) of those recruited for this study were from natural aquatic recreational locations within Australia.

A breakdown of aquatic settings in which each of the selected studies were conducted indicate that beaches and lakes as the most reported sampling locations. Nearly 70% of these studies included beaches (41.8%), lakes (27.9%) with other aquatic recreational waterbodies including dams (11.6%), streams (4.7%), and springs (4.7%), while estuaries, reservoirs, rivers and inlets represent 6.9% are also explored with less frequency. As a result, studies whereby faecal contamination remained the focus saltwater aquatic setting were dominant alternatively, for those studies focusing on cyanobacteria freshwater settings were most commonly explored.

Table 7. Summary of Selected Articles Included in This Systematic Literature Review

Article	Year & Location	Waterbody & activities	Study design/ contaminant	Health outcome/ symptoms	Results	Comments/ Limitations
Harrington et al., (1993)	1990-1991 Sydney, Australia	Beaches (six) High swimming frequency/ low swimming frequency and non-swimmers	Prospective cohort Faecal coliforms, feacal streptococci and Clostridium perfringens	General illness Respiratory illness Gastrointestinal illness	Those in any swimming category reported illness 1.63 times more often than non-swimmers. From all 43,175 swimming events recorded 14% could be attributable to an illness, with total illness and respiratory illness having the highest relative risk. The study lends no support to the concept of correlating health risk in swimmers with threshold levels of currently used bacterial indicator organisms.	1529 participants aged between 14-40 years self-reporting via questionnaire diaries. Potential reporting bias may therefore be evident. The study forms part of a health impact assessment of Sydney beaches relating to the deep-water effluent ocean outfalls.

Article	Year & Location	Waterbody & activities	Study design/ contaminant	Health outcome/ symptoms	Results	Comments/ Limitations
Lepesteur et al., (2006)	November 2002 – March 2003 Mandurah, Western Australia	Estuarine system Swam, wading, play in wet sand	Prospective cohort Faecal streptococci	Gastrointestinal illness Respiratory Illness Ear infection	This study suggested a relationship between incidence of disease and age group based on the recreational behaviour the different age groups exhibit. Linking faecal streptococci levels to the burden disease and excess illness rates in particular with the population of children engaging in aquatic based recreational activity. A correlation was established between microbial water quality and incidence of respiratory diseases for both children and adults	Children aged 15 and under made up 50% of sample group. 340 individuals recruited with a 76% retention rate at follow-up. Low study numbers may have contributed to a level of bias in results.

Article	Year & Location	Waterbody & activities	Study design/ contaminant	Health outcome/ symptoms	Results	Comments/ Limitations
Stewart, et al., (2006)	1999-2002 Southern Queensland Myall lakes New South Wales Florida (US)	Lakes, dams, catchment stream Aquatic recreational activities	Prospective cohort Cynotoxins-Microcystins, Saxitioxins, Cylindrospermopsin Faecal coliform	Varied -GI, RI	Findings suggest exposure to cyanobacteria based on total cell surface area above 12 mm^2/mL were more likely to report the incidence of symptoms particularly respiratory symptoms, than those exposed to waters where cyanobacterial cell surface areas were less than 2.4 mm^2/mL.	1331 participants provided sufficient data for analysis. The study population included both adults and children. Florida was included in the study with 16% of the sample population. No relationship was seen between faecal coliform counts in study waters and symptom reporting.

Article	Year & Location	Waterbody & activities	Study design/ contaminant	Health outcome/ symptoms	Results	Comments/ Limitations
Corbett et al. (1993)	Sydney, New South Wales	Beach/ocean swimming	Perspective cohort Faecal coliforms Faecal streptococci	Symptoms including vomiting, diarrhea, cough, cold, fever or flu symptoms, ear or eye infections	After exclusions (n= 2968). Of this 32.2% reported no swimming on interview day. 24.0% reported experiencing symptoms within 1 week of exposure. Swimmers were almost twice as likely as non-swimmers to report symptoms (after adjusting for age and sex). The prevalence of fever, respiratory, eye, ear and other symptoms increased with increasing measured bacterial counts on the day. Those swimming greater than 30 mins were 4.6 times more likely to develop GI symptoms than non-swimmers or those swimming less than 30 mins.	Participants >15yrs agree to initial beach interview and follow-up. No swimming previous 5 days and no illness preventing swimming volunteers, after exclusions (n= 2968).

Article	Year & Location	Waterbody & activities	Study design/ contaminant	Health outcome/ symptoms	Results	Comments/ Limitations
Pilotto et al., (1997)	1995 Goolwa, South Australia. Carcoar Dam New South Wales Hawkesbury River, New South Wales Lakes Narracan and Boga Victoria	Lake, dam, river Jet-skiing, water skiing, swimming and windsurfing	Perspective cohort Cyanobacteria including Microcystis aeruginosa, Microcystis sp., Anabaena sp., Aphanizomenon sp. and Nodularia spumigena. Hepatotoxins	Exposure symptoms including diarrhoea, vomiting, flue-like symptoms, skin rashes, mouth ulcers, fevers, ear and eye irritations	Exposure to cyanobacteria during recreational water-based activities was not found between the exposed and unexposed after two days. An association between exposure and symptom occurrence with duration of exposure at seven days. Participant exposure to 5000 cells per mL or more for one hour or greater had a significantly higher symptom occurrence rate than the unexposed.	Large variation in the number of unexposed (n= 75) to exposed (n=777). Some large C I variations Participants 6 years and over were involved in the study. The findings suggest that the current safety exposure threshold for exposure of 20, 000 cells per mL might be too high.

7.1.2 Study Design

Each of the selected articles utilised a prospective cohort study design as the chosen method of investigation. All of these observational studies followed a traditional cohort study design whereby studies recruited from a pre-determined setting, which in this instance was a natural recreational waterbody, in which exposure information at this time was also captured. Prüss (1998) notes that prospective cohort study designs are suitable approaches in examining the associations of interest despite the major limitations in composition variation for the exposure groups and the loss to follow-up.

Convenience sampling was commonly used within all selected studies in the recruitment of participants. Comparator groups, which were typically identified as non-swimmers or those experiencing low contact exposure were typically recruited through self-identification. The study by Harrington, Wilcox, Giles et al. (1993) was the only one to set requisite quotas in order to maintain equal numbers for high exposure and low exposure groups.

Face to face interviews guided by structured questionnaires were the most common method of pre-exposure data collection with the exception being self-administered questionnaires conducted in the Stewart, Webb, Schluter et al. (2006) study. Personal information including age, gender, health symptoms and status in addition to exposure activities, frequency and duration were typically recorded at this stage. Lepesteur, McComb, and Moore (2006) also included the sourcing and recording of observational data relating to identified exposure activities of participants, which offered subjective validation of the factors relating to the participant's exposure.

Post exposure follow-ups were commonly conducted via telephone interviews (4/5), while Harrington, Wilcox, Giles et al. (1993) favoured the use of individual participant questionnaire diaries which were submitted via regular mail upon bi-monthly completion. The time elapsed between exposure and post exposure follow-up varied between studies and was dependent upon the health ailment under investigation and the associated latency period. This varied from two days for Pilotto, Douglas, Burch et al. (1997) to 14 days for the Lepesteur, McComb, and Moore (2006) study with both symptoms and health outcomes explored.

From 2 days post exposure Harrington, Wilcox, Giles et al. (1993) explores GI illness, headache and vomiting and at 6 days for other illness categories; between 7-10 days after exposure Corbett, Rubin, Curry et al. (1993) explores for symptoms including vomiting, diarrhea, cough, cold, fever or symptoms suggestive of flu or ear or eye infections. Lepesteur, McComb, and Moore (2006) was interested from 14 days post exposure exploring clearly defined symptoms associated with respiratory and GI illness only. Stewart, Webb, Schluter et al. (2006) conducted follow-up telephonic interviews from three days post exposure based on health ailments related to ear, eye, GI, respiratory, cutaneous, fever and any symptom with each presenting symptom criteria. Pilotto, Douglas, Burch et al. (1997) conducted follow-up telephone sessions at day two and day seven post exposure to investigate possible symptoms relating to diarrhoea, vomiting, flu-like symptoms, skin rashes, mouth ulcers, fevers, eye or ear infections.

There were no selected studies which relied solely upon physician diagnosis to support or confirm the health status of participants in relation to self-reported symptoms or health outcomes. As a result, a reliance on participant self-reporting in identifying symptoms and illness outcomes could have introduced a level of self-reporting bias into the respective findings. Parental reporting bias may also be evident within the Lepesteur, McComb, and Moore (2006) study as parents completed follow-up questionnaires on behalf of their children which may demonstrate a degree of under reporting for example of minor or self-limiting illness.

7.1.3 Population Demographics

Of the selected articles 40% (n=2) maintained a research focus on adolescent and adult population groups. Three studies (60%) accounted for children within their selected cohort, with Pilotto, Douglas, Burch et al. (1997) recruiting from a minimum age of six years, Lepesteur, McComb, and Moore (2006) from only a ‘few weeks old’ and Stewart, Webb, Schluter et al. (2006) identifying children under 12 years. The paper by Lepesteur, McComb, and Moore (2006) specifically targeted family groups research which consequently allowed for the greatest variation in ages for participants (infants to 67 years) for each of the studies. For those studies reporting an exclusion of young children within the study cohort, barriers associated with ethical concerns relating to the recruitment and consent process were identified as the main prohibitive factors.

7.1.4 Study Size

Overall study sizes varied between the articles with the Lepesteur, McComb, and Moore (2006) study recruiting 340 subjects while the Corbett, Rubin, Curry et al. (1993) study recruited a total of 2,968 subjects. Across the five studies a total of 7020 participants were included with data from each represented in the overall findings. Large family groups recruited within the Lepesteur, McComb, and Moore (2006) study may have also contributed to a level of bias into the findings due to the creation of cluster illnesses considering the overall low number of total recruitments in the study.

7.1.5 Exposure Agent (contaminant)

Four of the five studies included in the systematic literature review identified faecal indicator bacteria including either or both streptococci and coliforms as the primary pathogen of investigation. Harrington, Wilcox, Giles et al. (1993) also included *Clostridium perfingens* as a pathogen of investigation in exploring faecal indicators and the associated impacts on human aquatic recreational exposure however, no reliable threshold levels were identified within this study. Of the four studies that focus primarily on the health impacts of faecal exposure and aquatic recreational settings 50% relate to investigation of point source contamination associated with ocean sewage outfalls at Sydney beaches.

Cyanobacteria was the primary agent of focus in 40% of the selected articles within this systematic review. Stewart, Webb, Schluter et al. (2006) explored cyanotoxin analysis including microcystins, saxitoxins and cylindrospermopsin in addition to faecal coliform sampling. Pilotto, Douglas, Burch et al. (1997) was interested in the exploration of cyanobacteria exposure, identified as blue green algae, during recreational water exposure on human health. Dominant sources of cyanobacteria observed were identified as *Microcystitis aeruginosa*, *Microcystis sp*., *Anabaena sp*., *Aphanizomenon sp*. and *Nodularia spumigena*.

Each of the studies selected within this systematic review clearly outlined the sample collection process pertaining to their specific system of investigation. All samples were analysed independently through accredited laboratories following Australian Standard prescribed techniques and subsequent reporting methods of results.

7.1.6 Exposure Activity

The contact exposure as identified by aquatic recreation activities varied somewhat between each individual study. Most of the studies (4/5) identified swimming specifically as an exposure activity, while Stewart, Webb, Schluter et al. (2006) simply presented a generalised description referring to ‘water contact activities’. Corbett, Rubin, Curry et al. (1993) was the only article to provide a formal definition of swimming within the context of their research as, ‘the immersion of the face and head in water’, while no other paper explicitly explored this or water ingesting while engaging in activities. Pilotto, Douglas, Burch et al. (1997) offered the greatest variety in aquatic recreational activities including those involving primary contact exposure, such as swimming and also secondary contact exposure activities including various motorised and non-motorised aquatic recreational equipment. Wading and playing in the wet sand above the shoreline were also noted as potential primary exposure activities included within the Lepesteur, McComb, and Moore (2006) study which would typically be applied to young children. Recommendations in consideration of the microbial standard for beach sand have been included within the revised WHO Guidelines on Recreational Water Quality (2021), currently no provisions exist within the National guidelines.

Corbett, Rubin, Curry et al. (1993) also inquired about exposure duration identified as the amount of time spent swimming. They identified a significant association between primary contact exposure duration and GI illness. It was noted that those who swam for greater than 30 minutes were 4.6 times more likely to experience GI symptoms than those who did not swim or swam of less than 30 minutes.

7.1.7 Illness and Health Outcome

In relation to enteric pathogens and the impact on human health after recreational exposure within natural waterbodies, 4/5 studies demonstrated mixed overall findings. Within the Stewart, Webb, Schluter et al. (2006) study there was no relationship found between the faecal coliform counts observed and symptom reporting by participants for GI, respiratory or the ‘any symptom’ category. However, limited information was provided within the article regarding indicator measures and any subsequent analysis therefore linking faecal pathogens and ill health will remain challenging.

An observed relationship between respiratory illness identified through participant self-disclosure of ear, nose and throat ailments expressed against measured levels of faecal streptococci were evident in exposure groups for both adults and children in the (Lepesteur et al., 2006). There was no similar relationship determined between streptococci exposure and GI illness in this study.

Recreational activities resulting in increased contact exposure and a higher incidence of illness were seen primarily in children aged 11-15 years who demonstrating a higher odds ratio (OR 4.23) compared to that seen in the closest age group of 0-5 years (OR 1.58). This younger age demographic was found to present high incidence rates for RI and GI which was suggested to be a result of their greater likelihood of sand and water ingestion as their activity was located at the shoreline.

An increase in relative risk (RR) for total and respiratory illness after exposure was observed by Harrington, Wilcox, Giles et al. (1993) however, this was not the case for GI illness. The RR (1.79, 95% C. I. 1.00-3.20) for reported total illness in males increased in high frequency beach swimmers when combined with non-ocean swimming. No significant increases in reported total illness were found for females with similar exposures to that of the male cohort. Participants exposed to any swimming category, that is either with a high or low level frequency reported an illness frequency of more than 1.6 times than that of non-swimmers. These findings do not lend support to the concept of correlating health risk with bacteria indicator threshold levels which at this time identified geometric mean for faecal coliforms as exceeding 300CFU/100ml or if one sample exceeds 2000 CFU/100mL.

Corbett, Rubin, Curry et al. (1993) found for Sydney beaches that swimmers demonstrated a greater liklihood than non-swimmers to report respiratory, ear and eye symptoms. The rate of symptoms increased marginally with higher levels of faecal contamination. GI illness was 4.6 times more likely to be reported in those who swam for longer than 30 minutes than non-swimmers or those who swam for less than 30 minutes however, no increase in symptoms were observed with an increase in recorded counts of faecal bacteria.

Swimmers were almost twice as likely as non-swimmers to self-report health symptoms after exposure. A notable association was also observed between water contamination and all reported symptom types with the exclusion of those associated with GI illness. However, findings cannot be extrapolated to include health outcomes in young children as those under the age of 15 years were excluded from the study.

The primary health risk for aquatic recreational participants specifically for cyanobacterial blooms comes from exposure to cyanotoxins. Cyanotoxin exposure has been identified to impact negatively on human health from exposure withing recreational and drinking water studies (Veal, Neelamraju, Wolff et al., 2018). However, there have been limited epidemiological studies with comprehensive study designs conducted focusing on cyanobacteria exposure and health impacts of Australian recreational waters. To date two prospective cohort studies have investigated the potential health impacts of recreational exposure to cyanobacteria at various natural aquatic waterbodies. Each of these studies have demonstrated clear associations between recreational exposure and negative health outcomes. Stewart, Webb, Schluter et al. (2006) examined 3,500 adults who were primarily participating in secondary contact exposure activities (personal water craft) in freshwater recreational settings within Queensland, NSW and Florida (US). Findings taken from program participants during follow up interviews conducted at least three days post exposure found a linear trend linking increased exposure levels with increased symptom reporting. It was observed that those using personal watercraft on lakes with higher recorded levels of cyanobacteria (cell surface area >12.0 mm^2/mL) were 1.7 (95% CI, 1.0 – 2.0) times more likely to report symptoms than those on lakes with low recorded cyanobacterial levels (cell surface area < 2.4 mm^2/mL). While this was observed across all health symptoms, it was more prominent with those symptoms relating to respiratory illness where those exposed to higher cyanobacterial levels were 2.1 times (95% CI, 1.1 – 4.0) likely to report symptoms than those exposed to lower cyanobacteria levels,

Results from this study however, may exhibit a degree of bias due to very low response rates (30%) during follow-up for participants in high cyanotoxin exposure sites. It is also noted that 80% of those participants identified as highly exposed to cyanobacteria levels were recreating at international locations.

Pilotto, Douglas, Burch et al. (1997) reported a significant association linking recreational water contact time, high cyanobacterial cell count exposure with minor self-limiting health ailments. Those participants with an exposure greater than 1 hour to cyanobacterial cell counts measured above 5,000 cells ml demonstrated increased levels of illness reporting compared to those identifying as no contact exposure. An observed dose response relationship with skin and eye sensitivities and adverse GI effects was also established (OR 3.44, 95% (CI), 1.09 – 10.82) within 7 days after exposure. This study demonstrated a lower threshold level for cyanobacterial exposure in natural recreational waterways of >5,000 cells per mL rather than the accepted 20,000 cells per mL, as it relates to symptom reporting.

8.0 Discussion

A wealth of international literature has been established over the past fifty years relating to the negative health impacts of human exposure to recreational surface waters impacted through harmful faecal pathogens. These pathogens consist of various enteric bacteria, viruses and protozoa from both human and animal sources and are introduced into a particular waterbody through either a point or non-point source processes. Much of the existing research into biological hazards associated with recreational waterways has focused primarily on human point source contamination, namely from ineffective wastewater practices, and the subsequent impact on human health upon contact exposure. In addition, a focus on adult population groups engaging in primary exposure recreational pursuits, with accidental water ingestion as the exposure pathway and GI illness as the health outcome remains the most common fields of investigation to date.

Recreational water quality in Australia is formulated nationally by the NHMRC through the ‘Guidelines for Managing Risks in Recreational Water’. While the guidelines do not hold any regulatory status, they are designed to provide an overarching framework in which to guide water management authorities at a local level. One component of these guidelines is in the monitoring and protection of public health specific to pathogenic and non-pathogenic waterborne miro-organisms, within the context of recreational aquatic settings. Routine sampling of recreational waterways for enteric waterborne bacteria and monitoring of potentially harmful cyanotoxins against nationally defined criteria provide the foundations in measuring associated health risk.

8.1 Health Impacts from Enteric pathogen Contamination in Recreational Water

A number of systematic reviews and meta-analysis have been conducted internationally with the aim of exploring health risks associated with waterborne pathogens in surface waters upon recreational exposure. A review of this literature has demonstrated overwhelming evidence in support of causal associations between recreational (swimming/bathing) exposure to waterbodies impacted by human wastewater and GI (Fleisher, Fleming, Solo-Gabriele et al., 2010; Leonard, Singer, Ukoumunne et al., 2018; Russo, Eftim, Goldstone et al., 2020; Wade, Pai, Eisenberg et al., 2003), RI (Harrington, Wilcox, Giles et al., 1993; Mannocci, La Torre, Spagnoli et al., 2016) skin related health outcomes (Fleisher, Fleming, Solo-Gabriele et al., 2010; Russo, Eftim, Goldstone et al., 2020; Yau, Wade, de Wilde et al., 2009) and any illness (Fleisher, Fleming, Solo-Gabriele et al., 2010; Leonard, Singer, Ukoumunne et al., 2018). Furthermore, epidemiological investigations into aquatic recreational exposure have demonstrated that GI illness is experienced at a higher rate in swimmers rather than non-swimmers at a variety of natural recreational settings including freshwater (Wade, Calderon, Brenner et al., 2008), marine (Arnold, Wade, Benjamin-Chung et al., 2016; Corbett, Rubin, Curry et al., 1993; Wade, Sams, Brenner et al., 2010) and riverine (Dale, Wolfe, Sinclair et al., 2009) waterbodies which are exposed to both point and non-point source contamination. Random control studies which assigned exposure (full head immersion) and non-exposure (no water contact) classifications to participants have also demonstrated that those exposed to recreational water known to be contaminated with human wastewater develop GI illness more often than those unexposed (Dorevitch, DeFlorio-Barker, Jones et al., 2015; Fleisher, Fleming, Solo-Gabriele et al., 2010; Kay, Fleisher, Salmon et al., 1994; Wiedenmann, Krüger, Dietz et al., 2006).

A longitudinal cohort study of 2, 811 Australians (Dale, Wolfe, Sinclair et al., 2009) explored the relationship between sporadic GI illness and multiple recreational swimming exposures across a variety swimming pool (treated) and natural (fresh and marine) aquatic settings. Finding of the study showed that a significant relationship was seen between GI symptoms and all swimming settings across the observed cohort. Analysis by age group indicated adults swimming at marine settings within the prior 14 days also demonstrated a significantly associated GI risk. It is important to note that self-reported GI symptoms were observed and no water analysis, recording of water ingested or exposure duration was conducted within the study which may have had some influence on overall findings. As a result, significant levels up bias may have been introduced and contributed to the final outcome of this study.

Despite a consensus within the international literature regarding the negative health impact of recreational aquatic exposure to enteric pathogens there remains a lack of uniformity in the selection of the most favourable indicator reference pathogen. A comprehensive review of epidemiological evidence focusing on health risks associated with poor microbiological quality of natural recreational waterbodies was conducted by Prüss (1998). Findings from this review demonstrated dose-related relationships in a large number of studies indicating a significant association (RR 1.0-3.0) between increased levels of indicator pathogens and an elevated GI health risk in swimmers (Prüss, 1998). It was observed that indicator organisms representing the closest association with GI illness for both marine and freshwater exposure were enterococci and faecal streptococci, while *E. coli* was also notes as a significant indicator for freshwater (Prüss, 1998). No significant relationship between measures of indicator bacteria and other minor self-limiting health outcomes were observed outside of those relating to GI illness in the review.

Similarly, a systematic review and meta-analysis was conducted by Wade, Pai, Eisenberg et al. (2003) on US faecal indicator measures concluding that, *enterococci* and *E coli* were better suited to assessing GI illness in recreational water exposures in comparison with alternative FIOs. While, Fleisher, Fleming, Solo-Gabriele et al. (2010) found supporting evidence demonstrating an appropriate dose-response relationship with increased enterococci exposure and dermal ailments no similar associations could be found to support that of GI and AFRI. Abdelzaher, Wright, Ortega et al. (2011) and Fleisher, Fleming, Solo-Gabriele et al. (2010) also add that for sub-tropical marine beaches a consistent relationship has failed to be drawn between enterococci and bather health for non-point source locations. The results for Australian studies conducted at Sydney beaches with known point source sewage contamination presented mixed findings. The study by Corbett, Rubin, Curry et al. (1993) suggested that faecal coliforms are somewhat favourable predictors of reported health (GI) symptoms than faecal streptococci while Harrington, Wilcox, Giles et al. (1993) concluded that faecal coliforms, faecal streptococci and *Clostridium perfingens* measures demonstrated a RR for total illness and RI but not for GI illness. Despite these inconsistencies in findings Australia, in support of WHO, consider enterococci alone as the appropriate indicator of bather health risk for all types of recreational waters (NHMRC, 2008; WHO, 2003; WHO, 2021). As the WHO confirm that "no statistical relationship has been established for *E. coli* that can support a dose–response guideline value" (WHO, 2021, p. xvi), enteric bacteria, which is also used as a proxy indicator for other potentially harmful pathogens (Almeida, González, Mallea et al., 2012; Senkbeil, Ahmed, Conrad et al., 2019) remains the primary reference tool for monitoring recreational water quality in Australia.

Epidemiological studies evaluating water quality as a predictor of self-limiting health outcomes following recreational exposure have generally addressed primary exposure activities such as swimming (with and without head immersion) rather than aquatic activities involving a range of water contact exposure. Consequently, only a limited number of small studies have addressed incidental contact from aquatic recreational activities, such as canoeing, wading, fishing, playing in wet sand at the shoreline, or boating. Activities involving no or minimal water contact also offer alternative avenues of pathogen exposure through inhalation of sea spray containing algal toxins, hand mouth exposure of riverine sand or soil and dermal exposure to potential biological hazards associated with beach sand. Russo, Eftim, Goldstone et al. (2020) recently attempted to somewhat address this void within the literature by conducting a systematic literature review and meta-analysis with the aim of investigating the risk of illness for aquatic recreational activities involving differing levels of contact exposure. It found that for these activities various factors such as activity intensity, frequency of participation, level of water contact and water quality played a cumulative role in determining the overall health risk. In general, as activities represented an increased uptake in any or all of these variables, increased health risks attributed to GI and RI were also observed.

Within Australia reporting of outbreak investigation, epidemiological research and exploratory case studies are somewhat limited in both volume and evidence quality compared to international comparisons, primarily over the past decade. In regard to the limited volume of information published in this field much has focused on swimming pools and is confined to specifically to jurisdictions on the eastern states of Australia. Waldron, Ferrari, Cheung-Kwok-Sang et al. (2011), reported on six waterborne outbreaks of cryptosporidiosis in New South Wales between 1990 and 2010, which were all associated with exposure to swimming pool environments. Similarly, Dale, Kirk, Sinclair et al. (2010) reported on waterborne outbreaks of GI in Australia between 2001 and 2007 from data collected within the OzFoodNet National foodborne disease surveillance network. During this measured timeframe it was reported that 6,515 GI outbreaks were recorded of which 78% were attributable to recreational water sources. All 42 waterborne GI outbreaks were associated with various types of swimming pool facilities with no outbreaks attributed to natural recreational waterbodies. These findings are somewhat at odds with comparative international results which demonstrate a reported higher case prevalence for waterborne ailments in natural aquatic recreational settings compared to Australia (Schets, De Roda Husman, & Havelaar, 2011; Wyn-Jones, Carducci, Cook et al., 2011) (Efstratiou, Ongerth, & Karanis, 2017; Graciaa, Cope, Roberts et al., 2018; Hlavsa, Roberts, Kahler et al., 2015; Yoder, Hlavsa, Craun et al., 2008). However, it is unclear whether this is implicated through the selection of specific indicator pathogens, methods in outbreak reporting or investigation, or some other undetermined factor.

8.2 Cyanobacterial and Algal Toxin Exposure in Recreational Waterways

Outside of enteric pathogens cyanobacteria and algal exposure is also an important consideration outlined by the WHO in relation to recreational waterbodies. Currently, the NHMRC's recreational water guidelines in Australia do not require routine sampling of recreational waterbodies in testing for cyanobacteria and algae regarding public health outcomes. As most cyanobacterial blooms are considered toxic, monitoring of waterways and providing notification of scums, and were considered appropriate, providing cell counts and density measures are deemed appropriate health protection measures. While no actual toxicity measures are conducted, a potential human health risk is therefore calculated based on the concentration for cyanobacteria within a specific waterbody (Falconer, 2001).

Cyanobacteria are inclusive of a broad range of prokaryotes that exist within specialised roles within the aquatic environment (Veal, Neelamraju, Wolff et al., 2018). They are naturally occurring with various species existing as part of most aquatic ecosystems including fresh, brackish, and marine water environments. Cyanotoxins are the active component of cyanobacteria which present as a health risk, in low numbers they may pose a minor self-limiting health risk upon exposure however, in larger numbers a much greater health risk is posed. Cyanotoxins have been shown to have hepatotoxic, neurotoxic, (Chamberlain, Marshall, & Keeler, 2019) and nephrotoxic (Veal, Neelamraju, Wolff et al., 2018) features with each targeting different body organs providing a range of potentially acute and chronic health outcomes in those people who come are exposed.

Cyanotoxins have the ability to enter the body through various routes of exposure including ingestion, immersion and inhalation of recreational waters. A wide range of symptoms have been identified after exposure including dermal, ocular, GI, and respiratory illness which can vary in the degree of severity (Veal, Neelamraju, Wolff et al., 2018). Of the few studies examining recreational exposure conducted under Australian conditions health symptoms relating to mild or self-limiting cases of GI, respiratory and cutaneous ailments have been identified as the most common (Falconer, 1999; Osborne, Shaw, & Webb, 2007; Pilotto, Douglas, Burch et al., 1997; Stewart, Webb, Schluter et al., 2006). In examining *L. majuscula* blooms in South-East Queensland Osbourne (2007) observed that the volume of time exposed to the associated toxins had a proportional impact with those reporting symptoms.

8.3 Point vs Non-Point Source Contamination

Human wastewater contamination and enteric pathogens remains the most commonly explored source of contamination regarding recreational water and human health. Sewer overflow (Hose, Murray, Gordon et al., 2005; Rodrigues & Cunha, 2017; Senkbeil, Ahmed, Conrad et al., 2019), broken sewage pipes (Hose, Murray, Gordon et al., 2005; Hughes, Beale, Dennis et al., 2017), defective onsite effluent treatment systems (Bradshaw, Snyder, Oladeinde et al., 2016; Hughes, Beale, Dennis et al., 2017; Rodrigues & Cunha, 2017; Senkbeil, Ahmed, Conrad et al., 2019), direct discharges from wastewater treatment plant outfalls (Bradshaw, Snyder, Oladeinde et al., 2016; Corbett, Rubin, Curry et al., 1993; Harrington, Wilcox, Giles et al., 1993) and human faecal discharge from boats (Rodrigues & Cunha, 2017) are popular sources of assessment within the international literature. Much of the Australian literature including those featured within this systematic literature review have focused on sewage ocean outfalls on the New South Wales (Sydney) coastline and the associated health impact on swimmers (Armstrong, Higham, Hudson et al., 1996; Ashbolt & Bruno, 2003; Bernard, 1989; Corbett, Rubin, Curry et al., 1993; Harrington, Wilcox, Giles et al., 1993; Kueh & Grohmann, 1989; Manning, Dixon, Birch et al., 2019). While limited research investigating pathogenic contamination of other natural waterways including rivers (Abbott, Lugg, Devine et al., 2011; Daly, Kolotelo, Schang et al., 2013; Gunady, Koutsoukos, & Theobald, 2016), ocean pools (Butler & Ferson, 1997), estuary (Henry, Schang, Kolotelo et al., 2016; Lepesteur, McComb, & Moore, 2006) and lakes (Roser, Davies, Ashbolt et al., 2006) including both point and non-point sources of contamination have been conducted.

8.4 Environmental and Animal Contamination Impacts

Further exploration into diffuse or non-point source contamination or recreational water in Australia and the potential human health impacts is an important yet under-explored research area for both pathogenic and non-pathogenic sources. The role of sand, soil and sediment in contributing to the promotion of biological contamination is also supported within the evidence of recent research (Ahmed, Wong, Chua et al., 2020; Brandão, Gangneux, Arikan-Akdagli et al., 2021; Fang, Vergara, Goh et al., 2018; Sabino, Rodrigues, Costa et al., 2014) and should be explored in more detail within a local context. Sabina et al., (2014) suggests that through neglecting to consider beach sand and restricting beach monitoring to include only water a potential gap is created in assessing the overall public health risks for users of the marine environment.

Inefficient urban infrastructure which intentionally or unwittingly diverts wastewater into natural waterways also used for recreational purposes, can also increase public health risk through increasing the exposure to waterborne pathogens. As a result, stormwater systems unintentionally present as key link in the spread of human and animal pathogens into natural aquatic recreational environments (Carney, Brown, Siboni et al., 2020). According to Sidhu, Hodgers, Ahmed et al. (2012), the role of stormwater run-off for example and the impact of microbial contaminants outside of FIB and the impact on natural recreational waterbodies is relatively unexplored in Australia.

The influence of enteric pathogens introduced through wildlife and domestic animals is also a focus are which derives further research focus as limited attention within an Australian public health context relating to natural recreational waterways has been examined. These variables should also be explored across various climactic zones within the nation including temperate and sub/tropical climates as differences in health risks have been observed within these environments (Abdelzaher, Wright, Ortega et al., 2011; Wade, Augustine, Griffin et al., 2018; World Health Organization, 2021). These considerations may become even more important within the context of national public health measure particularly in light of forecast climate change factors. Anticipated changes in temperature, rainfall, and extreme weather events may contribute favourably in increasing the burden of waterborne disease associate with recreational aquatic environments (Brandão, Weiskerger, Valério et al., 2022; Brouwer, Masters, & Eisenberg, 2018; Fujioka, Solo-Gabriele, Byappanahalli et al., 2015; Teixeira, Salvador, Brandão et al., 2020).

8.5 At-Risk Populations

A greater knowledge base into secondary exposure contact, behavioural influences and vulnerable population groups including young children and infants would also prove to be a valuable resource in better understanding the health risks of recreational water quality within an Australian context. As some evidence suggests that current recreational water guidelines both internationally and specific to Australia potentially underestimate the health risk to vulnerable population groups including children and infants (Leonard, Singer, Ukoumunne et al., 2018; Wade, Calderon, Brenner et al., 2008).

9.0 Conclusion

A systematic review of the existing literature has provided a detailed insight into the current status of human illness associated water quality and human health impacts for natural recreational waterways in Australia. A total of five related articles were selected for review and critique as they met the criteria set within the formalised search process. The microbiological focus of these studies was divided between health measures associated with enteric bacterial contamination of beach water from human sewage treatment facility outfalls and the remaining papers focused on the health impacts of cyanobacteria exposure of inland recreational waterways.

Much of the epidemiological research to date has focused primarily on beaches located within the Sydney metropolitan area and more specifically at sites which have known or suspected human sewage or wastewater contamination. It was also found, the most recent articles were conducted by Lepesteur et al., and Stewart et al., in 2006, which is approaching a twenty-year timespan since publication. The remaining articles were published in the mid 1990's which despite also exhibiting a lengthy time-gap, relate to findings undertaken prior to the implementation of the current NHMRC recreational water guidelines issued in 2008.

In review of the literature, a number of various knowledge gaps were identified, in particular those relating to diffuse sources of contamination, the human health impacts of faecal contamination from animal sources, the health impact of recreational water quality on vulnerable user groups and beach sand as a potential source of contamination for beachgoers. Consequently, these areas will be used in guiding a case study in the following section which will seek to examine these important variables, in an attempt to further understand the associated public health risks.

10.0 Reference List

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PART 3 - RISK ASSESSMENT

11.0 Introduction

Microbiological hazards associated with natural recreational waterbodies have the ability to create negative health outcomes upon exposure. As beaches in Australia remain popular leisure and recreational settings for the community especially during the warm summer months, ensuring these environments remain clean and safe remains an important public health priority. As previously mentioned, the NHMRC's guidelines for recreational water are the current overarching framework in which recreational water quality in Australia is managed. This serves in guiding water quality standards from a national level in support of reducing health risks associated with community recreational exposure.

The final section of this thesis involves a desktop case study assessing the human health risks associated with a common scenario, involving possible diffuse contaminant exposure within a recreational marine setting. Currently in Western Australia, many coastal local government authorities permit access of domestic pets onto beaches with their owners for the purpose of shared physical activity. As a result, potential faecal contamination from these animals, in this case dogs and horses, may be introduced into areas used for public recreation whereby, these pathogens are not typically encountered. This risk assessment will attempt to categorise the potential health risks for beachgoers exposed to domestic animal faecal pathogens contained in both marine water and beach sand.

Current NHMRC guideline are based on health risks associated with exposure to human faecal sources, with limited knowledge available relating to health outcomes associated with animal faecal pathogens in a marine environment. This investigation will include an analysis of both marine water and beach sand which is a novel approach in assessing health risk within this type of recreational setting. The risk assessment will be primarily guided by the Enhealth Environmental Health Risk Assessment framework (Priestly, Ong, Langley et al., 2012) and supported through the aligned stages of a Quantitative Microbial Risk Assessment (QMRA). It is proposed that an assigned measure of health risk will support each element within the case study and that recommendations will be provided at the conclusion in support of future public health developments in this field of investigation.

12.0 Background

In Australia coastal marine environments provide a setting in which a variety of recreational, sporting, and leisure activities, often involving many water-based activities are undertaken. These coastal recreational environments offer an inexpensive and accessible pathway in attracting different user groups of all ages, health status and socioeconomic backgrounds to engage in the natural environment. The most recent National Coastal Safety Survey reports that during the past twelve months 14.4 million Australians over the age of 16 years have visited the coast, averaging 3.3 visits per month (Surf Life Saving Australia, 2021). This relates to an estimated 500 million individual coastal visitations, with people spending on average 2.3 hours per visit with nearly half (48%) reporting swimming or wading as the most popular activity performed (Surf Life Saving Australia, 2021). Consequently, due to the significant number of the population engaging in recreational activities within marine water it is important to ensure water quality standards are maintained at safe levels so as not to create public health or safety concerns for those exposed within the community. While protective measures for aquatic based activities are undertaken through routine water quality monitoring no such practices are undertaken in ensuring microbiological status of beach sand is maintained in protection of land-based beach activities.

Surface waters used for the purpose of human recreation including fresh and coastal waters, have the ability to pose as a potential hazard to human health upon exposure. The microbial quality of surface waters is subject to frequent and dramatic changes as a result of biological contaminants from human, environmental and animal sources, which can subsequently increase human exposure to harmful waterborne pathogens potentially compromising public safety (Stec, Kosikowska, Mendrycka et al., 2022). Enteric pathogens including bacteria, virus and protozoa present in human faeces have been demonstrated as an immediate health risk to humans through recreational water exposure. The national focus for recreational water quality has typically focused on enteric pathogens from human sources via direct wastewater contamination (Weiskerger, Brandão, Ahmed et al., 2019) however, a risk burden from animal faeces may also present a degree of human health risk (Holcomb & Stewart, 2020; Korajkic, McMinn, & Harwood, 2018; McKee & Cruz, 2021) which is somewhat unexplored.

Enteric pathogens are naturally present within the intestines of warm-blooded animals and it is reasonable to conclude that contamination from both wild and domestic animals may also contribute more broadly to recreational water contamination. Zoonotic pathogens have also been identified as potential threats to human health through recreational water exposure however, the associated risk of transmission, infection and illness to beachgoers exposed to enteric pathogens from domestic canine and equine species is unclear. The potential illness risk associated with nonhuman faecal contamination is not clear due to inconclusive findings from the limited completed studies (Wu, Wang, Zhang et al., 2020). Consequently, developing a more comprehensive appreciation of the impact of various faecal sources on both recreational water quality and human health impacts is necessary for ongoing regulatory practices.

Marine water quality in Australia is assessed under the national recreational water quality guidelines (NHMRC, 2008) however, there exist no requirements for beach sand to also be routinely monitored. Current marine recreational water guidelines focus primarily on the measure of faecal indicator bacteria (FIB) namely enterococci, as the marker in determination of water quality and therefor public health outcomes in relation to exposure (Stec, Kosikowska, Mendrycka et al., 2022; Wyn-Jones, Carducci, Cook et al., 2011). Within these guidelines the assumption is made that a significant portion of waterborne pathogens originate from human origins. This may be a reasonable assumption for point source contamination however, questions have been made regarding this approach as it applies diffuse contamination cases. It has been suggested that this approach may misclassify the actual risk of exposure to pathogen concentrations and therefore reflect an inaccurate measure of public health (Wu, Wang, Zhang et al., 2020).

Research into health impacts among beachgoers has typically focused on illness associated with primary contact aquatic recreational activities and measured microbial water quality. Whitman, Harwood, Edge et al. (2014) however, posits that many beachgoers in fact tend to spend a great section of their time engaging in various active and passive pursuits on the sand, which may present a different dimension to public health hazards, as seen through traditional approaches to recreational water monitoring. Sabino, Rodrigues, Costa et al. (2014) argue that through a continuation of neglecting beach sand and confining marine recreational monitoring to include only water quality a potential gap is created in assessing the overall public health risks for users of beach environments. Through the implementation of this risk assessment, it will be argued that beach sand may also contribute as with recreational water to biological hazards imposing potential health risks to humans within recreational marine environments. Based on this understanding recommendations to support the inclusion of beach sand enteric pathogen monitoring into the Australian Recreational Water Guidelines where currently no requirements exist.

The primary focus of this risk assessment relates to ingested waterborne pathogens transmitted via the faecal-oral route and leading to GI illness in contrast with other recreational waterborne illnesses (Almeida, González, Mallea et al., 2012; McKee & Cruz, 2021). Research demonstrates that GI illness occurs at a higher rate than other illnesses in marine water than in freshwater for recreational exposure at a given level of FIB (Kay, Fleisher, Salmon et al., 1994; McKee & Cruz, 2021). Epidemiological research findings conducted in the US demonstrated that acute GI illness from recreational water contact associated with swimming and wading was found in 15 per 1000 individuals (DeFlorio-Barker, Wing, Jones et al., 2018; Weiskerger, Brandão, Ahmed et al., 2019). GI illness in Australia is typically seen as a temporary self-limiting condition defined by symptoms which Stec, Kosikowska, Mendrycka et al. (2022) describes as diarrhea, vomiting, stomach pain or nausea that may disrupt daily activities. The overall severity or illness risk depends on a number of different factors including the specific pathogen type, the dose and the general health condition of the individual as vulnerable population groups demonstrate an increased health risk upon exposure.

13.0 Risks and Hazards

A hazard is defined as, "the capacity of a specific agent to produce a particular type of adverse health or environmental effect" (Priestly, Ong, Langley et al., 2012, p. 16), it may therefore be viewed as a risk source but not necessarily as a 'risk' per se. A risk is seen more in terms of the likelihood of a measured health outcome in relation to a determined dose or concentration of an identified hazardous agent. While the term 'risk' takes on many different meanings within the realms of an identified field or discipline, within this context it is seen as,

> *"..... a function of the nature of the hazard, accessibility or avenues of contact (exposure potential), characteristics of exposed populations (receptors), and the likelihood of occurrence of exposures and consequences"(Kollura, 1996 cited in Choudhary & Neeli, 2018, p. 214).*

Consequently, a risk is the assessed probability of a determined health outcome for a person or group of people, within a nominated timeframe, for a specific agent it considers factors specific to the level of toxicity and exposure. In recent times the use of risk assessments as a tool in supporting evidence-based decision-making has become increasingly important as a more complex understanding of the potential impact of an agent or process towards a determined human health outcome is sought.

13.0 Risk Assessment Frameworks

There are many different tools and frameworks available that can assist in the assessment of risk as it relates to identified hazards and health-related outcomes. Within the context of an Australian setting the Environmental Health Risk Assessment (EHRA) framework has been developed by the Australian government in order to apply a structured process to assist in quantifying environmental health risk and hazard assessment as a function of public health promotion and protection. An EHRA according to enHealth (2002, p. xi), "provides a systematic approach for characterising the nature and magnitude of the risks associated with environmental health hazards". This process takes into consideration both the inherent hazards associated with a set of circumstances plus the specific conditions surrounding its contact with humans.

The current enHealth framework identifies five key areas within the risk assessment process, these are described as issue identification, hazard assessment, exposure assessment, risk characterisation and risk management. Refer to Figure 3. for an illustrative representation of where each section sits within the overarching framework. The first four areas within the enHealth framework will be used to guide this current risk assessment, with the final risk management step being substituted for a recommendations section. This risk assessment will be conducted to provide an insight into population level risk aligned with the nominated hazard exposures, namely faecal pathogens from domestic animal sources which may be encountered in recreational water and sand by beachgoers.

Figure 3. enHealth Risk Assessment Framework

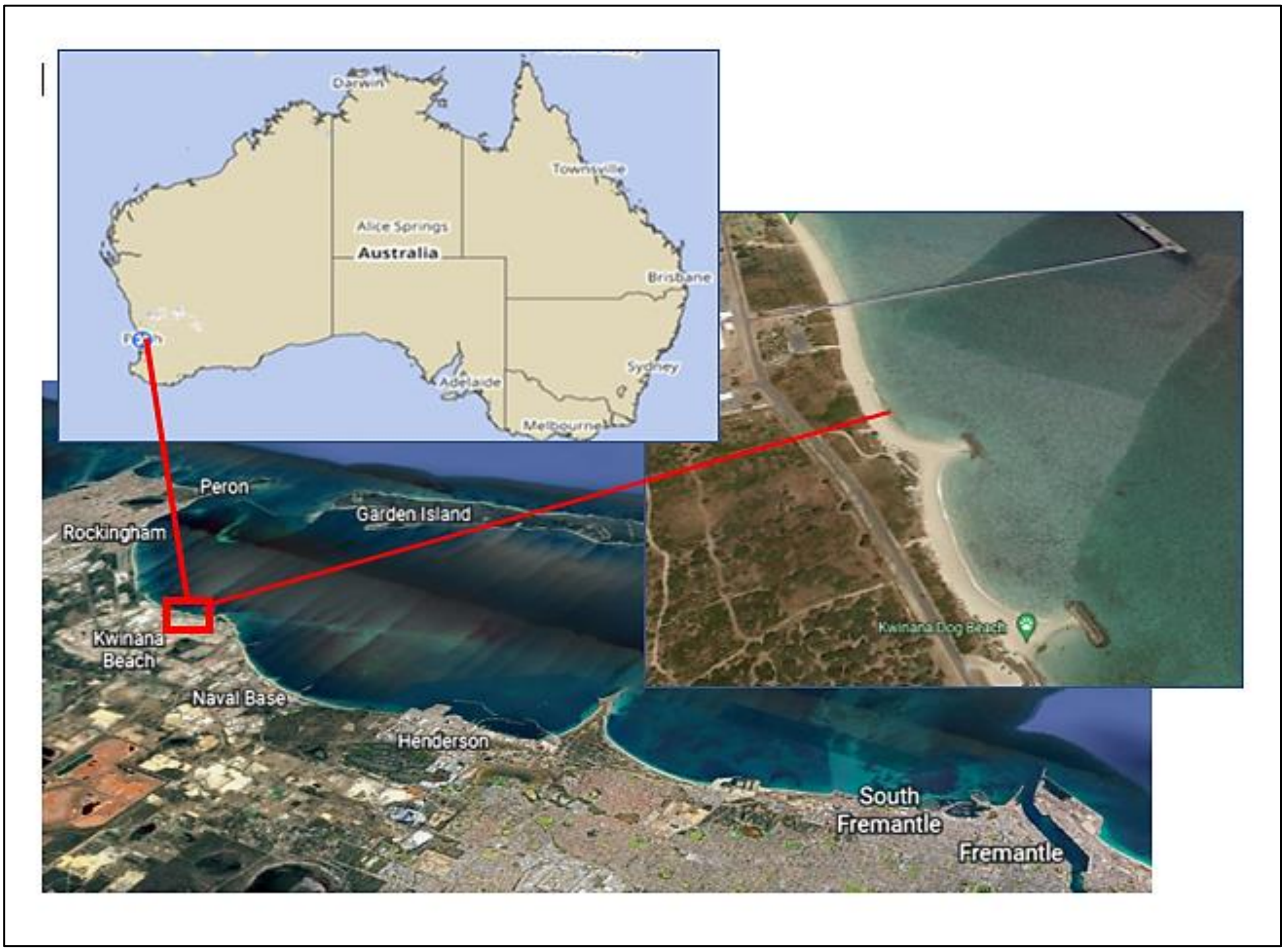
Figure removed due to copyright restriction

Source: Priestly, Ong, Langley et al. (2012).

14.0 Location Description

Kwinana (horse) Beach (32°25'68.22"S 115°75'04.00"E) and Kwinana Dog Beach (32°25'15.38"S 115°75'49.21"E) are adjoining beaches measuring a total liner distance of approximately 800m. Figure 4. presents a map providing a visual context and indicating the geographical location of the case site. They exist within the local government area (LGA) of the City of Rockingham, located on the Indian Ocean coastline 40km south of Perth, Western Australia. The beaches are bound by a groyne at the northern end of Kwinana Dog Beach and the Kwinana Grain Terminal on the southern side of Kwinana Beach. Rockingham Beach adjoins the southern side of the Kwinana Grain Terminal and proceeds a further 500m down the coastline. Rockingham Beach has a hazard rating of 3 out of 10 which is based on a safety classification system issued by Surf Life Saving Australia (Surf Life Saving Australia, n.d.). These beaches sit within the bounds of the environmentally sensitive Cockburn Sound precinct which is managed through the State Environmental (Cockburn Sound) Policy, 2015 and supported within the *Environmental Protection Act WA 1986.* The region is characterised by a Mediterranean climactic zone which typically resemble wet winters and hot dry summers (Abbott, Lugg, Devine et al., 2011). Peak seasonal swimming participation in this region of Western Australia is between late November to April where ocean water temperatures are more favourable in enticing beach-going recreational activity.

Figure 4. Map indicating geographical location of Dog/Horse Beach in the City of Rockingham, Western Australia



Source: (Google Earth, n.d.).

15.0 Research Question

Does exposure to marine aquatic recreational environments which are also promoted for shared use by domestic animals (dogs and horses) pose an increased public health risk due to the potential exposure of zoonotic enteric pathogens? A case study risk assessment of a Perth metropolitan beach.

16.0 Problem Formation/Issue Identification

Faecal contamination of the beach environment by domestic animals is a potential public health concern and has been underreported within the research literature both nationally and internationally. Domestic animals, primarily canine and equine species are permitted access with their owners onto some Perth metropolitan beaches for the purpose of shared physical activity. As outlined in findings from the systematic literature review conducted in Section 2, most research conducted relating to faecal contamination of recreational waterways in Australia relate primarily to those associated with point source contamination. Typically, this has focused on a narrow research area specific to ocean wastewater outflow systems which were common on Sydney beaches in the early 1990's as with Corbett, Rubin, Curry et al. (1993), Harrington, Wilcox, Giles et al. (1993) and Bernard (1989).

Within the international literature some level of attention has been directed towards exploring faecal contamination of recreational waters from farm animals (Soller, Schoen, Bartrand et al., 2010; USEPA, 2010) and sea birds (Schoen & Ashbolt, 2010; Soller, Schoen, Bartrand et al., 2010) through both direct and indirect means. These studies however, have remained focused on examining recreational water contamination and have not considered beach sand as a site of potential public health hazards. Recent attention both internationally and nationally has begun to be paid to exploring the potential health impacts faecally contaminated beach sand may have on beachgoers although findings remain limited.

16.1 Non-Point Source Contamination

It is suggested that there are currently more than 150 microorganisms that are derived from faecal sources of which many are also considered as waterborne pathogens (McLellan et al., 2013, cited in Henry et al., 2016). While they may be seen to pose varying levels of health risk to water users they also exist sporadically and at low level concentrations, making routine assessment somewhat problematic for recreational water management authorities (Henry, Schang, Kolotelo et al., 2016; McKee & Cruz, 2021). While direct screening of all harmful waterborne pathogens would be an ideal practice in protecting recreational water users, barriers relating to cost and time do not allow for this to be a viable option (Dorevitch, DeFlorio-Barker, Jones et al., 2015; Korajkic, McMinn, & Harwood, 2018). Consequently, alternative processes have been accepted and are applied such as the monitoring of faecal indicator bacteria (FIB) which are used in assessing the broader potential health risk for beachgoers exposed within these natural aquatic recreational environments.

FIB have been used based on the understanding that they are non-pathogenic, exist naturally in the gut, are shed in the faeces of warm-blooded animals, while also having been identified with illnesses associate with recreational swimming participation (Almeida, González, Mallea et al., 2012; Fewtrell & Kay, 2015; Napier, Haugland, Poole et al., 2017; Senkbeil, Ahmed, Conrad et al., 2019; Sidhu, Jagals, Smith et al., 2017). Research indicates that GI illnesses occur typically at higher rates than other illnesses including skin and respiratory ailments, as a result of water-based recreational exposure (McKee & Cruz, 2021). Based on this finding, it has been argued that water quality criteria directed towards public protection of GI illnesses will also prevent other common waterborne diseases (USEPA, 2012). As a result, FIB are used as representative indicators in determining levels of health risk in other bacterial, viral and protozoan pathogens potentially found within recreational waterbodies.

While the practice of using FIB as a proxy indicator for potential health risks associated with recreational waters worldwide there have also been various criticisms of this practice. Critics argue that it does not provide details regarding the source of the faecal contamination therefore, providing a limited understanding of the degree of health risk for recreational users (Ahmed, Sawant, Huygens et al., 2009; Sunger, Hamilton, Morgan et al., 2019). Another major criticism is presented by Sack, Oladunni, Gonchigoo et al. (2020) and Stewart, Gast, Fujioka et al. (2008) who argue that FIB including enterococci and e-coli are not well correlated with most common waterborne pathogens especially protozoan and enteric viruses and therefore remain unsuitable indicators in the wider detection of waterborne contaminants. This is even more pronounced outside of recreational waterbodies impacted by point source contamination, whereby contamination sources can be varied and from multiple species sources.

While waterbodies have remained the focus in routine monitoring FIB have also been found to occur in other aquatic sources that have not typically been associated with faecal contamination, including within sediment and aquatic flora (Ashbolt, Schoen, Soller et al., 2010; Sack, Oladunni, Gonchigoo et al., 2020; Stewart, Gast, Fujioka et al., 2008). It is also noted that some FIB (enterococci) may exist as a part of a normal aquatic ecosystem and also have the capacity to replicate without a host in environmental settings under certain conditions (Holcomb & Stewart, 2020; McKee & Cruz, 2021; Teixeira, Salvador, Brandão et al., 2020). Beach sands in tropical, subtropical and temperate climates for example, have also been observed to demonstrate high levels of indicator bacteria including enterococci and E. coli despite the existence of any known sources of human or animal contamination (Abdelzaher, Wright, Ortega et al., 2011; Fleisher, Fleming, Solo-Gabriele et al., 2010; Sack, Oladunni, Gonchigoo et al., 2020; Stewart, Gast, Fujioka et al., 2008). Moreover, it was also found that traditional FIB such as enterococci or *E. coli* have a faster decay rate than other bacterial and viral pathogens in aquatic conditions (Korajkic, McMinn, & Harwood, 2018; Sack, Oladunni, Gonchigoo et al., 2020) and maintain the ability to live longer in beach sand than beach water (Hartz, Cuvelier, Nowosielski et al., 2008).

In consideration of these factors (Verhougstraete, Pogreba-Brown, Reynolds et al., 2020) suggests that quality assessments should be based on accumulative variables including the types of pathogens present in the environmental setting, climate and geographical setting (tropical vs. temperate) in order to generate a more accurate risk profile. Working within the boundaries of current recreational water guidelines a false indication of faecal pollution may be presented, generating a misleading assessment of the true presence and subsequent risk level of associated pathogens (Almeida, González, Mallea et al., 2012; Hughes, Beale, Dennis et al., 2017; Leonard, Singer, Ukoumunne et al., 2018). Without a comprehensive understanding of the contributing factors in recreational waterbody contamination meaningful classifications cannot be assigned, inhibiting a true appreciation of human health risk and any attempts in manage it (Ahmed, Wong, Chua et al., 2020).

16.2 Faecal Contamination from Animal Sources

The health risks associated with exposure to point source contamination has been well explored within the academic literature and this knowledge helps form the foundation to current WHO and Australian recreational water guidelines. In attempts to generate a greater understanding of potential biological health risks in aquatic recreational environments further efforts have also been applied in understanding the health risks associated with non-point source contamination. This in part involves exploring other forms of potential faecal contamination sources, including various native and domestic animal species, which remains largely unexplored especially within Australia. Consequently, limited attention has been directed towards understanding the human health impact of exposure to enteric pathogens from domestic animals within recreational marine environments.

The human health risks associated with waterborne enteric pathogens differ based on a variety of contributing factors including the source species responsible for the contamination. Traditionally, faecal contamination of human origin was seen to present the greatest health burden due to the host-specificity of pathogens and this belief was supported in both research and risk management practices. Dufour, Wade, and Kay (2012) for example, in reviewing research in this area conducted prior to 2010 found no conclusive evidence in supporting swimming-associated GI illness from recreational exposure to natural waterbodies impacted with faeces from non-human sources. Others including Soller, Schoen, Varghese et al. (2014) and Zimmer-Faust, Steele, Griffith et al. (2020) reason that health risk is not as great in non-human sources of FIB due to a reduced overall pathogenic load, compared to that of human sources. This approach however, has not been supported by Harwood et al., (2017, cited in Korajkic, McMinn, & Harwood, 2018) who demonstrates that FIB levels typically found in human faeces range between 10^5–10^9 CFU per gram, while depending on the species, those found in animal excreta range from 10^4 to 10^7 CFU per gram. Based on this, it would appear that comparable pathogenic loads, at least in the context of FIB exist and similar health impacts and subsequent risk associations should therefore be equally applied within the context of recreational water contamination.

Recently conducted research indicates that avian faeces may be a leading cause of increased faecal indicator levels in both recreational waters and beach sand (Bonilla, Nowosielski, Cuvelier et al., 2007; Wright, Solo-Gabriele, Elmir et al., 2009). In a study comparing the amount of enterococci shed through faeces from humans verses animals at a beach environment, Wright, Solo-Gabriele, Elmir et al. (2009) found that the contribution from dogs far exceeded those recorded from human or bird shedding. During this study Wright, Solo-Gabriele, Elmir et al. (2009) concluded that the FIB shed from "one dog faeces equated to 1,872 people, and 6,940 bird faeces". Despite the lower number of dogs observed, a larger overall faecal mass, coupled with a greater contribution of enterococci per faecal event resulted in a greater overall observed hazard. Similar findings were also reported by Wang, Solo-Gabriele, Abdelzaher et al. (2010) in investigating enterococci estimates from bird and dog visitations at a US beach, where birds were found to contribute between 10^3-10^5 CFU/day, while dogs were responsible for a greater load of between 10^9-10^{10} CFU/day. Cox, Griffith, Angles et al. (2005) also identify that pathogen and faecal indicator concentrations in domestic animal faeces were generally higher than that of wild animal faeces, demonstrating potentially an increased level of health risk. Consequently, the findings from these studies support the understanding that domestic animals rather than wildlife, which was claimed by Converse, Kinzelman, Sams et al. (2012) and others, as a dominant contributor of diffuse faecal contamination of recreational marine environments.

International research also highlights that those exposed to recreational waters contaminated with animal faeces are likely to experience similar GI illness outcomes at those exposed to recreational water contaminated with human wastewater. A study on marine bathing in New Zealand by McBride et al., (1998, cited in Soller, Schoen, Bartrand et al., 2010) demonstrated that illness risks presented through exposure to animal faecal material was largely similar to that experienced as through exposure to human faecal material. It has been proposed that enteric pathogens from ruminant animals, including cows and sheep also pose an elevated health risk compared to other animal species due to a higher risk of zoonotic transferability with humans (Soller, Schoen, Bartrand et al., 2010). However, research contributed by Cox, Griffith, Angles et al. (2005), Wang, Solo-Gabriele, Abdelzaher et al. (2010) and Wright, Solo-Gabriele, Elmir et al. (2009) found that faecal sources evident in recreational waterbodies may contribute an equally similar health risk to humans upon exposure. As a result, in exploring diffuse sources of recreational water contamination a greater understanding of associated health impacts would also serve as an important function in public health planning and protection.

16.3 Beach Sand, Soil & Sediment

Human exposure to faecal contamination through recreational waters has remained an active area of investigation internationally during the past five decades however, faecal contamination of beach sand and the associated exposures and potential human health impacts have remained relatively unexplored. As with recreational waters, beach sand and sediment can also be impacted by various direct and indirect sources of biological contamination (Rodrigues & Cunha, 2017; Weiskerger, Brandão, Ahmed et al., 2019). Research findings have also linked human exposure of faecally contaminated beach sand to increased risk of negative health outcomes associated with GI, skin, respiratory and other illness (Bonilla, Nowosielski, Cuvelier et al., 2007; Halliday & Gast, 2011; Heaney, Sams, Dufour et al., 2012). However, while such findings may be seen to demonstrate associated exposure response relationships with faecally contaminated beach sand and human illness there remain many unknown factors which may contribute to this process.

Pathogenic and non-pathogenic microbes can occur ubiquitously in natural aquatic habitats within the sediment, biofilms and sand particles (Ahmed, Wong, Chua et al., 2020; Neave, Luter, Padovan et al., 2014; Weiskerger, Brandão, Ahmed et al., 2019) or be introduced through human, domestic or wild animal sources (Heaney, Sams, Dufour et al., 2012; Whiley, Austin, da Silva et al., 2017; Whitman, Harwood, Edge et al., 2014; WHO, 2021). Evidence under both environmental and laboratory conditions indicate that beach sand can harbour greater FIB levels than the adjacent water, and that submerged, foreshore and backshore sand contact can increase the risk of illness for humans (Brandão, Weiskerger, Valério et al., 2022; Craig, Fallowfield, & Cromar, 2004; Fewtrell & Kay, 2015; Heaney, Exum, Dufour et al., 2014). Whitman, Harwood, Edge et al. (2014) also observed in their analysis of FIB densities in beach sand that greater pathogen densities were evident in these samples than in those observed from water located at the same beaches. It is argued that beach sand may provide more favourable conditions in supporting faecal pathogens than recreational water with studies conducted by Halliday and Gast (2011) in the US showing FIB density in sand between 2-38 fold greater than that of water.

Evidence suggests that beach sand (Bonilla, Nowosielski, Cuvelier et al., 2007; Sabino, Rodrigues, Costa et al., 2014; Solo-Gabriele, Harwood, Kay et al., 2016; Whitman, Harwood, Edge et al., 2014) and soil/sediment (Ahmed, Payyappat, Cassidy et al., 2020; Fang, Vergara, Goh et al., 2018; Sidhu, Jagals, Smith et al., 2017) associated with aquatic environments acts as a reservoir providing favourable conditions in supporting FIO's. Optimal environmental conditions including temperature, protection from UV light and access to nutrients provide microbes with a variety of favourable conditions which contribute in support of growth, survival and proliferation (Ahmed, Payyappat, Cassidy et al., 2020; Bonilla, Nowosielski, Cuvelier et al., 2007; Bradshaw, Snyder, Oladeinde et al., 2016; Halliday & Gast, 2011; Heaney, Exum, Dufour et al., 2014; Weiskerger, Brandão, Ahmed et al., 2019). The large surface areas and the composition of the beach sand grains are believed to act as a natural filter trapping and accumulating microorganisms shed by both humans and animals (Bonilla, Nowosielski, Cuvelier et al., 2007; Whitman, Harwood, Edge et al., 2014) allowing them to increase in concentration and therefore toxicity (Daly, Kolotelo, Schang et al., 2013; Rodrigues & Cunha, 2017). Microbes may then be transferred, suspended or relocated to either sand or water through processes including wave actions, rain events or through human or animal traffic beyond the immediate location of contamination (Abdelzaher, Wright, Ortega et al., 2011; Craig, Fallowfield, & Cromar, 2004; Daly, Kolotelo, Schang et al., 2013; Fleisher, Fleming, Solo-Gabriele et al., 2010; Sabino, Rodrigues, Costa et al., 2014; Solo-Gabriele, Harwood, Kay et al., 2016). This may therefore place hazardous enteric pathogens in closer contact with beachgoers, subsequently increasing the overall public health risk.

Transport and relocation of contaminated beach sand has also been demonstrated to have a potential impact on increasing the risk of human exposure. During a translocational study of gull droppings on beach sand Bonilla, Nowosielski, Cuvelier et al. (2007) found that outside of any notable traffic or weather disturbances a single gull dropping can impact an area of $3.1m^2$ of dry sand. Moreover, it was demonstrated that bacterial sized particles in high traffic areas can be relocated up to five metres from the original site of contamination within a 4 hour time period (Bonilla, Nowosielski, Cuvelier et al., 2007). This may therefore place hazardous enteric pathogens in closer contact with beachgoers, again increasing the overall public health risk.

In analysing FIO levels of proportionate samples of beach sand and marine water, it was found that wet sand maintained 100 times greater and on average 1000 times greater for dry sand than those seen in comparative water sampling (Bonilla, Nowosielski, Cuvelier et al., 2007). Similar observations were also reported by Ahmed, Payyappat, Cassidy et al. (2020) who found FIB in recreational waterbody sediment to be 1000-10,000 times greater than that contained in overlying water. In a comprehensive review of associated research Halliday and Gast (2011) also found similar results with FIB up to 38 times greater in wet sand than in associated bathing waters. In contrast, Whiley, Austin, da Silva et al. (2017) observed enterococci levels to be at higher levels for samples taken in closer proximity to the sand dunes rather than the tidal area however, it was reported that recent rain events and low sample numbers may have impacted findings.

Epidemiological investigations into beach sand contact among beachgoers have found a positive association with enteric illness including elevated risk of diarrhea and GI illness which is influenced by both age and activity. Research findings from Heaney, Sams, Dufour et al. (2012) and Heaney, Sams, Wing et al. (2009) demonstrate this risk to be increased in the order of between 20–50% especially for activities which involved digging or being buried in the sand. These findings are in support of Bonilla, Nowosielski, Cuvelier et al. (2007) who demonstrated an increased burden of GI illness and diarrhea in beachgoers in the US who spend more time engaging with wet sand than those in the study who did not.

17.0 Hazard Assessment

There are a number of waterborne pathogens which are seen to present as potential hazards upon exposure within a recreational aquatic environment and could be seen as a potential public health risk to beachgoers. Within this risk assessment there will be four waterborne zoonotic pathogens considered including two enteric bacteria (*Salmonella*, and *Campylobacter*) and two enteric protozoa (*Cryptosporidium* and *Giardia*). These were chosen as representative pathogens as they have been identified internationally as leading causes GI illness from recreational water exposure. GI illness is seen as a significant contributor towards recreational waterborne morbidity and has therefore been selected as the primary health outcome under consideration within this risk assessment.

18.0 Hazard Identification

Numerous international studies have been shown to reveal a causal relationship between measured levels of faecal indicator organisms (FIOs) within recreational water exposure and GI symptoms. Studies involving the epidemiological investigation of aquatic recreation have demonstrated consistently that swimmers develop GI illness at a greater frequency than non-swimmers at marine environments (Arnold et al., 2013; Colford et al., 2007; Wade et al., 2010). Controlled exposure studies, which randomly assign participants to either an exposure or non-exposure group have also demonstrated that water-exposed individuals are more likely to develop GI illness than those unexposed (Dorevitch, DeFlorio-Barker, Jones et al., 2015; Fleisher, Fleming, Solo-Gabriele et al., 2010; Kay, Fleisher, Salmon et al., 1994; Wiedenmann, Krüger, Dietz et al., 2006). A Canadian study recently concluded that the estimated proportion of waterborne cases linked to recreational water exposure was 22.0% for campylobacteriosis, 18.7% for cryptosporidiosis, and 32.1% for giardiasis cases. Similarly, Gibney, O'Toole, Sinclair et al. (2017) in examining suspected waterborne outbreaks reported in Australia between 2001 and 2007 found 78% to be attributable to recreational water compared to 19% for drinking water. This therefore demonstrates the potential community health burden and the subsequent need to further understand the underpinning factors contributing to the biological hazards associated with recreational marine environments in Australia.

18.1 Zoonotic Pathogens, Domestic Animals and Beach Contamination

The human health exposure risks from recreational waters impacted by non-human pathogen sources is not as clearly understood in comparison to those from human sources. Research findings to date have demonstrated conflicting outcomes, with some studies unable to demonstrate significant links between faecally contaminated recreational waterbodies from animal sources and human health risk levels (Colford, Wade, Schiff et al., 2007), while others show clear associations (McBride, Salmond, Bandaranayake et al., 1998).

Zoonoses are an important yet commonly overlooked hazard in relation to recreational water contamination in Australia. In general terms, the World Health Organization (2020) defines zoonoses as, those infections or diseases in which humans and animals are both susceptible and that could be transmitted directly in either direction from either species, or indirectly (Haider, Rothman-Ostrow, Osman et al., 2020; Rees, Minter, Edmunds et al., 2021) via food or the environment. Zoonotic diseases can be associate with bacterial, viral and protozoa sources, with Taylor., (2001, cited in Sack, Oladunni, Gonchigoo et al., 2020) reporting that they account for more than 60% of infectious agents and 75% of emerging diseases worldwide. They are also representative of a broad spectrum of health outcomes, from minor self-limiting ailments to serious life-threatening conditions, which demonstrates the ranging impact inter species pathogens can have on public health outcomes.

The exposure pathway in human contamination of zoonotic enteric waterborne pathogens may be seen in the form of direct contact with infected animals or indirectly through exposure to beach sand or recreational marine water infiltrated by infected animal faecal material. Within a marine environment this may also be likely in the form of various processes including through sand or soil leaching, run-off during rainfall and by direct de-posit of faecal material by animals (Turgeon, 2012). Domestic fauna such as dogs and horses, can contribute to human health risk in shared recreational settings through the shedding of contaminated faecal material. These animals can therefore introduce and spread enteric zoonotic pathogens into areas used for human recreational activity which may not otherwise be exposed, creating an avenue for additional human health risk.

18.1.1 Domestic Canine Contamination Sources

The relationship and close interaction shared between humans and domestic dogs may be seen to contribute to the increased risk in transmission of zoonoses from companion animal to human

(Papini, Marangi, Mancianti et al., 2009). With this understanding, and in consideration of the claim by Lykov, Pavlova, and Rudova (2021), that over 23 million different microorganisms are present in a single gram of excrement, enteric pathogens from canine sources become an important etiological consideration within aquatic recreational environments. A limited number of studies have attempted to explore this topic internationally including within recreational marine (Valério, Santos, Teixeira et al., 2022; Wright, Solo-Gabriele, Elmir et al., 2009), and urban park environments (Grimason, Smith, Parker et al., 1993; Procter, Pearl, Finley et al., 2014; Rahim, Barrios, McKee et al., 2018). While limited attention has previously been directed in this area of potential public health concern, the previously mentioned studies provide some useful insight into the current field of investigation. However, the extent to which domestic canine species in Australia contribute to the faecal contamination of aquatic recreational marine environments is unknown and details relating to how this may impact human health also remain unclear.

Domestic canine species have been shown to carry a variety of harmful pathogens, such as *E coli, Campylobacter jejuni, Salmonella* spp., and *Giardia lamdia* which can be presented in both symptomatic and asymptomatic form (Bataller, García-Romero, Llobat et al., 2020; Rahim, Barrios, McKee et al., 2018; Rukambile, Sintchenko, Muscatello et al., 2019; Uiterwijk, Nijsse, Kooyman et al., 2018)**.** Studies exploring the shedding of pathogenic agents from canines in dog parks in Canada found between 6.4% and 25% of faecal samples contained *Giardia spp.,* 15% *Cryptosporidium spp*., 1.2% *Salmonella spp*. and 43% *Campylobacter spp*. (Procter, Pearl, Finley et al., 2014; Smith, Semeniuk, Kutz et al., 2014). In exploring asymptomatic domestic dogs as a source of potential human infection in Spain, Bataller, García-Romero, Llobat et al. (2020) in completing faecal examinations, found a prevalence of *Salmonella spp. of 1.8%* in reportedly health dogs housed in a variety of domestic locations. Papini, Marangi, Mancianti et al. (2009) found that 30.8% of dog faeces located within urban green areas such as parks, playing fields, verges of a central Italian region contained *Giardia* cysts. Furthermore, it was also demonstrated that dogs in this study were shedding up to 1428 cysts per gram (CPG) of faeces within the areas of investigation, which can continue to be shed over an extended location and time period (Rosa, Gomes, Mundim et al., 2007). Grimason, Smith, Parker et al. (1993) investigated the occurrence of *Giardia spp.* cysts and *Cryptosporidium spp.* oocysts in dog faeces at seven public parks in the West of Scotland identifying that *Giardia* cysts were present in 11% of samples, while *cryptosporidium spp*. oocysts were located in 1% of faecal samples. While it would appear that dogs are a likely source of potentially harmful zoonotic pathogens (Green, White, Kelty et al., 2014) inconsistencies and uncertainties exist within the literature defining the types of pathogens and the density of specific pathogens within the excrement of domestic dog species.

18.1.2 Domestic Equine (Horse) Species as a Contamination Source

As with domestic canine species, horses are also seen to share a close connection with humans, with riding being a popular recreational pursuit in Australia (Lönker, Fechner, & Wahed, 2020). The introduction of horses into areas also used by humans for aquatic recreation creates an opportunity for increased exposure to faecal pathogens. This may be in the form of direct contamination from faecal material or indirectly through leachate and runoff from horse waste which can contaminate surface water acting as an exposure route for beachgoers (Western Australia Water and Rivers Commission, 2002). However, limited information within the academic literature relating to the microbial burden of equine faeces, potential impacts on recreational watercourses and the role of domestic equine species in zoonotic enteric pathogen transmission. This lack of research and knowledge therefore hinders the level of understanding within the context of human health impacts (Moriarty, Downing, Bellamy et al., 2015).

A wide variety of viral, bacterial and parasitic zoonotic diseases have the ability to affect horses, occurring as mild self-limiting infection through to more acute forms infection and illness (Khurana, Dhama, Prasad et al., 2015). According to Paruch and Paruch (2022), there are currently

56 zoonotic pathogens that have been identified in horses, of which over 40% were bacteria, including *Salmonella* and *E. coli* and 9% were protozoa, including *Cryptosporidium* and *Giardia*. A recent systematic review of equine zoonotic pathogen transmission conducted by Sack, Oladunni, Gonchigoo et al. (2020) identified oral, inhalation and cutaneous sources as the primary exposure route, with ingestion manifested through GI symptoms as the most common infection outcome.

Research relating to the zoonotic transfer of pathogens and associated health outcomes within aquatic recreational environments is extremely limited within an Australian context. However, some international evidence is available with studies conducted into zoonotic contamination in veterinary students which may assist in providing some foundational guidance in enteric pathogens associated with domestic equine spp. and human health outcomes. An Italian study involving a small sample cohort of veterinary students working in close contact with foals each had symptoms supporting a *C. parvum* diagnosis, which Galuppi, Piva, Castagnetti et al. (2016) used in support of evidence outlining zoonotic transmission between the species. Bender and Tsukayama (2004) demonstrated similar findings in a veterinary teaching hospital where two students were diagnosed with *salmonella* infection which was associated with previous equine cases. Some overseas evidence supporting *giardia* (Santín, Cortés Vecino, & Fayer, 2013), *cryptosporidium* (An, Wang, Pu et al., 2020) and *campylobacter* (An, Wang, Pu et al., 2020; Moriarty, Downing, Bellamy et al., 2015) infection has also been presented in horses primarily showing with no clinical signs.

The prevalence of zoonotic microorganisms in horse faeces has been shown to vary greatly between pathogens and between individual studies. Studies enumerating *E. coli* have reported a variation in mean concentrations of between 1.2 x 10^5 CFU/g dry weight (Moriarty, Downing, Bellamy et al., 2015) to 3.0 x 10^5 CFU/g wet weight (Weaver, Entry, & Graves, 2005). Khurana, Dhama, Prasad et al. (2015) report that horses impacted by asymptomatic cryptosporidiosis maintain a shedding rate of *oocysts* of up to 21%, while Xiao and Herd, (1994, cited in Khurana, Dhama, Prasad et al., 2015) maintain asymptomatic shedding of *Giardia* in one quarter of adult horses. In a recent pilot study investigating faecal pathogens in healthy horses, Paruch and Paruch (2022) found a high detection rate for protozoan parasites with *C. parvum* (4.47×10^2 copies) and *G. lamblia* (7.77×10^6 copies), while low level average detection was noted for *C. jejuni* (22.4 copies$\cdot$g^{-1} faeces). These studies highlight the diversity of findings relating the pathogen presence and density currently observed within the faecal material of horses.

The Western Australia Water and Rivers Commission (2002), estimates that a standard light horse (450 kg) produces approximately 15kg per day of solid (wet) manure, with An, Wang, Pu et al. (2020) outlining that there is currently no standard practice for the collection of faecal waste of horses when outside of typical pasture grazing and stable management hygiene. Consequently, faecal droppings are commonly abandoned in the environment which provide avenues for contamination and potential infection of those who come in contact with the material.

18.2 Waterborne Enteric Bacteria

There are four key enteric waterborne pathogens responsible for GI infection and illness that have been included within this risk assessment. Each of these pathogens have been reported in the faeces of domestic canine and equine species to varying levels, while also being noted as maintaining zoonotic capabilities for humans upon exposure. Demonstrating low infectious doses, a short incubation period and transmitted through the faecal-oral route present as favourable conditions in perpetuating the life cycle and human health risk properties of these enteric pathogens. While exposure may demonstrate a health risk to the general population, at risk populations are seen to include pregnant women, children, the elderly and immunocompromised persons (Sanborn & Takaro, 2013). An overview of each of these pathogens will now follow.

18.2.2 Salmonella

The major habitat of Salmonella is within the intestinal tract of humans and animals however, it has also been identified within the environment as a result of animal and human excrement. Salmonella has been known to survive in extreme conditions for several months (Pond, 2005) and has been observed to survive for extended periods in water and soils (Ford, Moffatt, Fearnley et al., 2018).

Salmonella bacteria are responsible for a range of illnesses which result in asymptomatic to symptomatic infections (Pond, 2005; USEPA, 2009). Most infections presenting as mild, brief, and self-limited (Pond, 2005)**,** with clinical symptoms of non-typhoidal salmonellosis may include nausea, diarrhea, abdominal cramps, chills, and fever which last from four to seven days from infection (Pond, 2005; Sanborn & Takaro, 2013).

Salmonella is typically associated with foodborne infection associated with poultry and livestock (Ford, Moffatt, Fearnley et al., 2018) however, it has also been identified in groundwaters including those used for human recreational purposes (USEPA, 2009). Recreational water contamination can occur through the excretion of pathogenic micro-organisms by humans and animals (Ashbolt, 1996, as cited in Pond, 2005). -The incidence of *salmonella spp.* infection in Australia is estimated to be 185 infections per 100,000 population per year (Ford, Moffatt, Fearnley et al., 2018). Salmonellosis is also classified as a notifiable disease in Australia.

18.2.3 Campylobacter

Campylobacter spp. can survive under adverse environmental conditions where it has been observed in aquatic environments with low temperatures (4°C) up to 4 months (Pitkanen & Hanninen, 2017). Pond (2005) notes that beach sediment may also act as a reservoir for campylobacters during cooler seasonal periods.

Studies have demonstrated *Campylobacter* as a major cause of human infections (Nichols, Richardson, Sheppard et al., 2012) and for developed nations this transpires primarily as acute self-limiting enteritis and gastroenteritis in adults and children (Facciolà, Riso, Avventuroso et al., 2017; Ghasemzadeh & Namazi, 2015). This is generally characterised with symptoms aligned with acute, self-limiting gastroenteritis, including watery diarrhea, fever and abdominal pain lasting between 2-10 days (Magana-Arachchi & Wanigatunge, 2020; Pond, 2005; Sanborn & Takaro, 2013)**.**

Research has indicated that animals can act as potential reservoirs for human infections indicating that animal hosts are the main sources associated with food and water contamination (Magana-Arachchi & Wanigatunge, 2020; Shrestha, Midwinter, Marshall et al., 2019)**.** A number of domestic animals have also been identified as hosts for *Campylobacter spp*. including dogs which Chaban, Ngeleka, and Hill (2010) identify can contain up to 106 CFU within their faeces.

Potential also exists for *Campylobacte*r to cause recreational water-related illness through exposure to human and animal waste, although few waterborne outbreaks have been formally reported internationally (Pitkanen & Hanninen, 2017; Pond, 2005; USEPA, 2009).

18.3 Waterborne Enteric Protozoa

As with the previous enteric bacteria reference pathogens, giardia and cryptosporidium also maintain low infectious doses and short incubation periods making them highly contagious upon exposure (Ayi, 2015; Papini, Marangi, Mancianti et al., 2009; Perkins & Trimmier, 2017; Zahedi, Monis, Deere et al., 2021). The faecal oral route is the most common method of transmission for these pathogens.

18.3.1 Giardias

Recreational water exposure is a proven risk factor for giardiasis through the accidental ingestion of contaminated water impacted by the infected faeces of humans and animals (de Roda Husman & Schets, 2010; Pond, 2005; USEPA, 2009). Boarato-David, Guimarães, and Cacciò (2017) identifying zoonotic transfer from domestic animals including dogs as a highly viable factor in human contamination as infected animal can excrete between 10^1 to 10^6 cysts per gram of faeces. Once secreted cysts become immediately infective and can also survive in a variety of environmental conditions (Magana-Arachchi & Wanigatunge, 2020; Papini, Marangi, Mancianti et al., 2009) where at low temperatures **(**4° C) they have been observed to remain infective in water for 11 weeks, in soil for 7 weeks and 1 week in cattle faeces (USEPA, 2009).

Giardiasis is primarily transmitted via the faecal–oral route through the consumption contaminated food or water, or through contact with the infected faeces of human or animals (Boarato-David, Guimarães, & Cacciò, 2017 ; Hamilton, Waso, Reyneke et al., 2018; Magana-Arachchi & Wanigatunge, 2020)**.** Symptoms such as abdominal pain and cramps, diarrhea, weight loss and bloating may become evident (Ayi, 2015; Boarato-David, Guimarães, & Cacciò, 2017 ; Magana-Arachchi & Wanigatunge, 2020; Sanborn & Takaro, 2013) and typically last from one to several weeks (Pond, 2005). Those with immune deficiencies and children under 5 years of age (Sanborn & Takaro, 2013) have a greater likelihood of developing prolonged or more moderately severe health outcomes (Perkins & Trimmier, 2017; Pond, 2005).

18.3.2 Cryptosporidium

Excreted Cryptosporidium oocysts can survive for extended periods in animal wastes, water and soils (Chahal, van den Akker, Young et al., 2016). While they cannot reproduce outside a host they can be transported from contaminated runoff entering surface waters resulting in potential human exposures (Chahal, van den Akker, Young et al., 2016; Wohlsen, Bates, Gray et al., 2006).

The major routes of transmission include water, food and person-to-person contact however, it is acknowledged that respiratory transmission is also possible (Magana-Arachchi & Wanigatunge, 2020; Waldron, Ferrari, Cheung-Kwok-Sang et al., 2011)**.** Symptoms typically include diarrhea, nausea, and abdominal pain (Chahal, van den Akker, Young et al., 2016) which can last for up to a number of weeks. The risk of adverse health effects from infection is seen as very unlikely however, acute illness may be prolonged and moderate illness severity may be experience in young children or those immunocompromised persons (Greenwood & Reid, 2020; Magana-Arachchi & Wanigatunge, 2020; Pond, 2005; Putignani & Menichella, 2010).

Cryptosporidiosis is common in Australia with an annual incidence of 22 illnesses per 100,000 in Australia (Lal, Hales, French et al., 2012; Ryan, Lawler, & Reid, 2017) however, it is reported that many cases remain undiagnosed and therefore a true rate cannot be confirmed. Cryptosporidium have been detected in various types of natural waterways used for recreational activities in Australia at levels ranging from 0.004 to 16.2 cysts L^{-1} of water analysed (Hamilton, Waso, Reyneke et al., 2018).

18.4 Hazard Identification - Limitations and Uncertainties

Outbreak data, especially in relation to waterborne cases involving recreational waterways is limited in Australia. Events involving gastroenteritis be be difficult for health professionals to identify, as illness can often present as mild and self-limiting whereby people may not seek medical attention. As a result, many waterborne outbreaks may go unrecognised never being identified. Consequently, the true burden of GI illness in relation to marine recreational environments is not fully understood.

The extent to which domestic dogs and horses contribute to faecal contamination of recreational marine water is largely unknown. This knowledge gap therefore also extends to the potential zoonotic transfer of faecal pathogens to humans and the associated potential health outcomes within this setting. This human-infectivity uncertainty has been identified as a common knowledge gap experienced with many zoonotic pathogen species in relation to environmental sources like beach sand and water. Maintaining a strong understanding of this relationship is important as it can have a significant impact on the outcome of a health assessment. Schoen (2010) notes the importance by suggesting a focus on future research into ‘specifying pathogen densities and genotypes’ in better understanding the impact of faecal contamination associated with recreational beaches.

There also exists numerous unknowns in relation to the behaviour and survival of faecal pathogens in environmental marine waters (McKee & Cruz, 2021). Developing a comprehensive knowledge of environmental factors such as salinity, pH, temperature, nutrients and light, on the survival and proliferation of the nominated reference pathogens would proves as important factors in understanding potential exposure and consequent health risks.

Marine sites consist of dynamic interfaces between shore and water, providing a diverse microbial habitat that can vary greatly across spatial and temporal parameters (Weiskerger et al 2019). As such, considerations in determination of pathogen contamination levels associated with beach sand and water require the incorporation of many complex independent and inter-related factors many of which are unknowns. Within the current risk assessment, it is presented that the conditions of fresh faecal contamination only support the associated health risk outcomes.

One of the main considerations with conducting a health-based risk assessment is that due to various uncertainties a number of assumptions need to be made with respect to exposures. As within the current risk assessment there have been no sampling or measured undertaken on location and outcomes have been drawn from the available published literature, which may not necessarily match with the environmental conditions evident at the site of the case study.

19.0 Dose- Response Assessment

Exposure is just one of a number of variables needed in measuring human health risk with other dependent variables such as organism pathogenicity, the virulence of individual strains, concentration of pathogen, exposure route and individual susceptibility as equally important determining factors (Dorevitch, Ashbolt, Ferguson et al., 2010; Korajkic, McMinn, & Harwood, 2018; Rahim, Barrios, McKee et al., 2018; Rodrigues & Cunha, 2017). The infectious dose refers to the number of organisms of a specific pathogen needed to infect an individual (Stec, Kosikowska, Mendrycka et al., 2022) however, it is important to note that infection does not necessarily translate to illness. The infectious dose of enteric pathogens varies, with protozoan pathogens this generally exists at a medium level while for bacterial pathogens a higher dose is typically required (Graciaa, Cope, Roberts et al., 2018; Korajkic, McMinn, & Harwood, 2018).

A dose-response analysis is used with the aid of mathematical models to determine the probability of a predetermined health end-point given a known dose, usually measured as infection or in some instances illness. They attempt to describe the dose-response relationship for specific pathogens, routes of transmission and hosts (World Health Organization, 2016) with the aim of translating these exposures into risk classifications. Stochastic dose-response models have been employed within this risk assessment and they are based on the underlying assumption that infection can occur at any dose, with the likelihood increasing as the dose increases (Abe, Takeoka, Fuchisawa et al., 2021; Rahman, Munther, Fazil et al., 2018). Within this format, probabilities are determined at an individual level through events that are treated as random occurrences. The most common models used within QMRA are the exponential (EM), the exact beta-Poisson (EBPM) and approximate beta-Poisson models (ABPM).

The exposure unit is typically referred to as a "dose", which identifies a specified number of pathogens that directly associates with the degree of exposure. Dose is representative of the volume of water or sand ingested and exposure is estimated through pathogen loading. Despite dose-response models being commonly employed in QMRA assessments in determining health risk associated with recreational water quality, dose-response relationships relating to pathogens in beach sand and human illness are not well developed (Heaney, Sams, Dufour et al., 2012; Whitman, Przybyla-Kelly, Shively et al., 2009). Consequently, for the purpose of this risk assessment dose-response estimates constructed for swimming water will be used in exploring GI risk in beach sand exposure.

The equation used to calculate dose estimates is presented as equation 1. This is important within the risk assessment process in quantifying various contributing factors in determination of an overall marker in which to evaluate a perceived or undetermined level of health risk.

Dose equation- $$d^{S}_{rp} = \frac{C_{ENT}}{R^{S}_{ENT(rp)} \times 100} \times R^{S}_{rp} \times V, \qquad \text{(Equation 1)}$$

Where d^S_{rp} refers to the overall exposure dose of each reference pathogen *(rp)* in units of CFU or (oo)cysts from each source *(s)*, C_{ENT} is the concentration of enterococci (CFU $100mL^{-1}$/g), $R^S_{ENT(rp)}$ is the density of *rp* enterococci per *s*, R^S_{rp} is the density of *rp* for each *s*, V is the volume of water or sand ingested (*g* or *mL)*. Refer to table 7 for a list of corresponding substitute features used in constructing the estimated dose, which are sources through the published literature.

Table 8. Parameters used for calculation of estimated reference pathogen dose in both dog and horse faeces.

	Input Variable for Dose Equation	**Reference**
$\mathbf{C_{ENT}}$	Enterococci- 200/100 mL	(NHMRC, 2008)
$\mathbf{R^S_{ENT(rp)}}$	Dog- 1.13×10^4 CFU/g ww	(Wright, Solo-Gabriele, Elmir et al., 2009)
	Horse- 2.55×10^5 CFU/g ww	(Moriarty, Downing, Bellamy et al., 2015)
$\mathbf{R^S_{rp}}$	Various	Refer to Figure Table 8
V	Water- 0.025L	(EnHealth, 2012)
	Sand- 0.05L	(EnHealth, 2012)

The 200/100 mL value for enterococci concentration is noted as greater than the threshold of illness transmission reported in the majority of studies attempting to define a NOAEL or LOAEL for GI illness. The upper 95th percentile value of 200/100 mL is identified as the average probability of one case of gastroenteritis in 20 exposures (NHMRC, 2008). This was chosen as hypothetical FIB level for both water and sand samples within the risk assessment, as this is noted as the higher range of the acceptable level of exposure within the current Australian recreational water guidelines.

Table 9 Summary Description of Selected Enteric Pathogens for Equine and Canine spp. Applied to the Risk Assessment.

	Microorganism	*Common Source*	*Health Ailment*	*Horse*	*Dog*
Bacteria	Salmonella spp. (e.g., *S. typhi*)	Humans and domestic animals	Salmonellosis, gastroenteritis,	$5.45 x 10^1$g (Paruch & Paruch, 2022)	10^2 x 10^6 g^{-1} (Tanaka, Katsube, & Imaizumi, 1976)
	Campylobacter spp. (*C. jejuni),*	Sewage, domestic, wild animal faeces	Gastroenteritis, campylobacteriosis	2.16 $x10^5$g (Moriarty, Downing, Bellamy et al., 2015)	10^3–10^6 cfu/g^{-1} (Chaban, Ngeleka, & Hill, 2010)
Protozoa	Cryptosporidium oocysts	Human, animal faeces	Cryptosporidiosis, respiratory disease,	*C. parvum* 4.47 X 10^2g (Paruch & Paruch, 2022)	1.6 $x10^2$ oocysts/g (Grimason, Smith, Parker et al., 1993)
	Giardia *duodenalis* (cysts)	Human & domestic animal faeces	Giardiasis, abdominal cramps	1.6 × 10^4 g^{-1} (Cox, Griffith, Angles et al., 2005)	5.4 $x10^3$g (Uiterwijk, Nijsse, Kooyman et al., 2018)

Source: Adapted from Rodrigues and Cunha (2017)

The parameters used within these models are derived from the literature and generated through a combination of clinical, pathological and outbreak data. These models fall within the ideology of the single-hit theory which is based on the understanding that each ingested pathogen particle is assumed to act independently and therefore has an individual probability of causing infection (WHO, 2016). In the context of QMRA Haas, Rose, and Gerba (1999) argues that Beta-Poisson models are more appropriate in evaluating enteropathogenic bacteria, while exponential models are suited more for enteropathogenic protozoa analysis (Haas, Rose, & Gerba, 2014), this approach will also therefore be adopted within the current risk assessment.

The exponential model in determination of the probability of infection given a dose *d* is given as;

$$P_{inf}(d) = 1 - \exp(-rd), \qquad \textbf{(equation 2)}$$

where *r*, refers to the constant and *d* is the calculated exposure dose.

Each pathogen is understood to have an independent and equal probability (*d)* to survive and cause infection in the host (Brown, Graham, Soller et al., 2017; Chandrasekaran & Jiang, 2019). The dose response data for *cryptosporidium* and *giardia* have been fit with the exponential model.

In the case of both *Salmonella* and *campylobacter*, *r* is not constant among human hosts and is therefore more accurately defined via a beta distribution. An alternative to the exact beta-Poisson model is the approximate beta-Poisson model (Haas, Rose, & Gerba, 2014) which is often used within QMRA as it avoids some of the mathematical complexities associated with the former model. An important characteristic of both models is the ability to maintain functional (linear) consistency at low doses which is a key feature in exploring microbial risk assessment (Rahman, Munther, Fazil et al., 2018; Xie, Roiko, Stratton et al., 2017). The application of this model is typically subject to the general rules: $\alpha \ll \beta$ and $\beta \gg 1$ (Rahman, Munther, Fazil et al., 2018; Xie, Roiko, Stratton et al., 2017) or $\alpha \ll N_{50}$ and $N_{50} \geq 1$ (Weir, Mitchell, Flynn et al., 2017). Some beta Poisson models (EBPM) also use N_{50} within the model equation rather than a β constant, in this instance N_{50} simply refers to an estimate of the median infectious dose. The approximate beta-Poisson model is defined as,

$$P_{inf}(d) = 1 - (1 + d/\beta)^{\alpha}, \qquad \textbf{(equation 3)}$$

where each pathogen has an independent and equal probability (*d)* to survive and cause infection in the host, *d* represents the dose, β and α are constants. Refer to Table 9 for a list of corresponding substitute features which are sources through the literature.

Table 10. Dose-response model parameters used for substitution.

	Pathogen	Dose Response Model	Constants	Reference
Bacteria	Campylobacter jejuni	Beta Poisson	α = 0.145 and β = 7.59	(Medema, Teunis, Havelaar et al., 1996)
	Salmonella (nontyphoid)	Beta-Poisson	α = 0.3126 β = 2885	(Haas, Rose, & Gerba, 1999)
Protozoa	Cryptosporidium	Exponential	r = 0.09	(USEPA, 2005)
	Giardia	Exponential	r = 0.0199	(Rose, Haas, & Regli, 1991)

19.1 Dose-Response - Uncertainties and limitations

One limitation of the current risk assessment is that only consideration of fresh faecal contamination was applied as a result the effects of aging for pathogens in consideration of normal environmental factors. This may have impacts on virulence, pathogen load and infectivity of reference pathogens which may also impact associated measured health outcomes.

Large variability was also observed within the literature relating to measured pathogen loads within the faecal samples of both horses and dogs. This would potentially impact on the process used to determine dose calculations as within equation 1. Due to natural and environmental variability such as dilution, advection, and die-off (Soller, Schoen, Bartrand et al., 2010) modelling range parameters in estimation of dose calculation could provide more accurate estimates for dose variation.

Dose–response modelling aims to predict the probability of human infection following the ingestion of a single pathogen however in reality, encountering a single pathogen is unlikely and the effects of recreational exposure to multiple and simultaneous pathogen exposures are limited (Lykov, Pavlova, & Rudova, 2021). As suggested by Schoen and Ashbolt (2010), recreational marine waters can be contaminated by a mixture of more than one pathogen source and this can have a varied and unknown response for each individual.

The heterogeneous nature of pathogens in marine water and beach sand may mean that an individual sample is not representative of prevailing microbial levels either temporally or spatially (Henry, Schang, Kolotelo et al., 2016). As a result, providing probabilistic exposure modelling incorporating a range of variables for each dose-response input may provide greater precision in formulating health risk outcome measures.

Due to limited published dose-response studies for children on both sand and beach water and the reference pathogens selected for use within this risk assessment findings are restricted to those potentially experienced with adults only. Based on these finding for the adult population it is argued that the level of exposure risk for children may under-represent the overall health impacts.

20.0 Exposure Assessment

Individuals can develop infections through a variety of ways, the World Health Organization (2021) notes that exposure of mucous membranes, through accidental ingestion or inhalation during recreational water activities is the most common route of exposure to enteric and non-enteric hazards. Analysis of outbreak investigations in the US have demonstrated that head immersion is an important risk factor in increasing the risk of illness as it relates to recreational water exposure (Sinclair, Jones, & Gerba, 2009). Swallowing water while swimming, either purposeful or accidental, can present as a factor in increasing the health risk for waterborne pathogens (Stec, Kosikowska, Mendrycka et al., 2022).

20.1 Exposure Types

The level of potential health risk associated with biological contaminant exposure within a recreational waterbody is influenced by the type and concentration of pathogens, in addition to the degree of contact a person has with those pathogens (Russo, Eftim, Goldstone et al., 2020). These factors are impacted by activity type, skill level of the individual, the amount of exposure time and the route in which the organism enters the body. The exposure routes of recreational water pathogens typically involve three primary formats including direct dermal contact, ingestion, and inhalation (Rodrigues & Cunha, 2017) with ocular ailments also noted (McKee & Cruz, 2021). In essence, this translates to infections or health ailments involving the skin, upper respiratory tract, GI tract, ear and eye (Almeida, González, Mallea et al., 2012; Hose, Murray, Gordon et al., 2005; Leonard, Singer, Ukoumunne et al., 2018; Mannocci, La Torre, Spagnoli et al., 2016; McKee & Cruz, 2021; Sinclair, Jones, & Gerba, 2009).

The level of contact exposure to potentially infectious or toxic agents in recreational water is also dependent on the degree of water contact experienced by the individual (Russo, Eftim, Goldstone et al., 2020). The World Health Organization (2021) and the NHMRC (2008) have categorised aquatic recreational activities based on the level of risk associated with the degree of water contact. Marine recreational environments are classified into three distinct categories according to the level of exposure with the prescribed waterbody, these include 'no contact', 'incidental contact', and 'whole body contact'. No contact exposure is described as recreational activities which involve no direct contact with water however exposure and inhalation of sea spray may occur, this may include children playing on beach sand. Incidental contact (secondary contact) is a category assigned to those aquatic recreational activities where typically only the limbs are in direct contact with the water and a greater degree of contact is atypical, this may include fishing, wading and some watercraft activities. Whole-body contact (primary contact) incorporates those activities which typically enact full body immersion, or where swallowing water is likely. This may include activities such as swimming, surfing, snorkelling and sailboarding. It is also important to note that inadvertent immersion such as slipping into water or being swept into water by a wave is also considered within this classification (NHMRC, 2008; WHO, 2021).

20.2 Contaminant Ingestion

While it is acknowledged that various routes of exposure and subsequent health ailments are associated with biological recreational water contamination the focus of this risk assessment is for pathogens transmitted via the faecal-oral route and associated with gastrointestinal (GI) illnesses. This includes the ingestion of pathogens contained within recreational water and beach sand during the course of normal recreational beach activity for adults. Behavioural conditions such as pica, which involve extreme rates of ingestion of substances with no nutritional value, such as beach sand have been excluded from this risk assessment.

20.2.1 Recreational Water

While head immersion has been an acknowledged risk factor there exists within the literature some inconsistency regarding accepted ingestion rates during participation in recreational activity. The WHO Guidelines for Safe Recreational Water Environments (WHO, 2003) estimate that "20-30ml of water is swallowed per hour of swimming activity". Research conducted by Dufour, Evans, Behymer, et al. (2006) into swimming pool water ingestion found that the mean volume ingested for children (≤ 18 years) was 37ml during 45 minutes exposure, while for adults this was shown to be considerably less at 16ml. The study also suggested that similar results could also be expressed for fresh water swimmers due to similarities in behaviours relating to activity and head immersion however, no further evidence was provided to support this claim. Schets, Schijven, and de Roda Husman (2011) also demonstrated similar results regarding adult and child ingestion additionally they also provided additional gender analysis ingestion rates for adults. "Dependent on the water type, men swallowed on average 27-34 ml per swimming event, women 18-23 ml, and children 31-51 ml" (Schets, Schijven, & de Roda Husman, 2011). However, this sits in contrast with Koreivienė, Anne, Kasperovičienė et al. (2014) "who calculated that a swimmer can be expected to imbibe up to 50–200 mL of water in one recreational session". Current Australian recommendations indicate an average of 50 mL/hr for children under 15 years of age and for those 15 years and greater an average of ingested water while swimming of 25 mL/hr (EnHealth, 2012).

20.2.2 Beach Sand

Investigation into beach sand at marine environments and the impact on human health outcomes is a relatively recent focus area within academic literature. Early epidemiological studies by Bonilla, Nowosielski, Cuvelier et al. (2007) and Heaney, Sams, Wing et al. (2009) into the health risks of sand contact for beachgoers has highlighted a hazard which was previously overlooked within recreational marine environments.

The WHO (2003) noted that beach sand exposure was seen as a potential source of contamination which had the ability to impact on human health outcomes. At this time, limits to appropriate research findings with supporting dose-response relationships resulted in the WHO declaring insufficient evidence in supporting a valid threshold level as with recreational water. The WHO (2021) within the recently revised guidelines have advised of a provisional recommendation for beach sand of 60CFU/g for enterococci however, this is yet to be adopted within the current Australian recreational water guidelines.

To date, limited research has been conducted regarding routes of transmission including ingestion for beach sand has been conducted both nationally and internationally. Hand-mouth transfer is an important component in exploring contamination via the faecal-oral route of exposure of beach sand however, limited public research is available on the topic especially for adult populations. In addition, ingestion volumes for beach sand are also absent from the literature. While differences are evident, soil ingestion volumes have been adopted as a proxy for beach sand values as a result of the limited availability of supporting evidence. Current Australian exposure factor guidelines for outdoor soil ingestion for those 15 years of age and above is for 50mg per day (EnHealth, 2012), which has been adopted for the current risk assessment.

20.3 Vulnerable Population Groups

Exposure to harmful microbiological hazards while engaging in aquatic recreational activities have also been shown to have greater health impacts on vulnerable population groups compared with the general population. Those groups at an increased risk of illness include children younger than 10 years of age, the elderly, pregnant women and the immunocompromised, who can face consequences of waterborne pathogenic infections which can be more serious and potentially life threatening (Mannocci, La Torre, Spagnoli et al., 2016; WHO, 2021). There is limited published research into waterborne infection of vulnerable population groups when exposed to natural recreational waterbodies in Australia. As a result, it is important to rely predominately on risk modelling and international studies in order to provide some national standards guidance.

International studies primarily from Europe and the US have evidenced repeatedly that children are disproportionately affected by waterborne pathogen outbreaks at-higher rates of illness than adults exposed to comparable aquatic recreational conditions (Prüss, 1998; Russo, Eftim, Goldstone et al., 2020; Sinclair, Jones, & Gerba, 2009; Wade, Sams, Brenner et al., 2010). Similarly, Heaney, Sams, Dufour et al. (2012) has also demonstrated an increased risk of GI illness in children exposed to beach sand over adults. Some studies have demonstrated a relationship between contamination levels of recreational water and increased rates of overall illness and some specific disease including, GI ailments among younger swimmers (Sinclair, Jones, & Gerba, 2009). This has been identified in both enteric pathogens such as enterococci when exceeding 158 CFU/100ml (Verhougstraete, Pogreba-Brown, Reynolds et al., 2020) and with cyanotoxin exposure (Veal, Neelamraju, Wolff et al., 2018).

It has been reported that children are more susceptible to waterborne infection and disease for a given exposure compared to adults (Sanborn & Takaro, 2013; Verhougstraete, Pogreba-Brown, Reynolds et al., 2020). It has been argued that this is due to factors including those relating to under-developed immune system, toxicological susceptibility, physiological and behavioural factors (DeFlorio-Barker, Arnold, Sams et al., 2018; Ferguson, Del Donno, Obeng-Gyasi et al., 2019; Sinclair, Jones, & Gerba, 2009). Once infection is activated Veal, Neelamraju, Wolff et al. (2018) note that a smaller body size is more susceptible to the risk of contamination but may also serve in prolonging and increasing the severity of illness on body systems.

Research investigating the behavioural patterns of children suggest an increased risk of infection to exposure levels through each of the three common routes of exposures, ingestion, dermal, and inhalation. Compared with adults, children are more likely to play for longer in recreational waters (DeFlorio-Barker, Wing, Jones et al., 2018; Fewtrell & Kay, 2015; Stec, Kosikowska, Mendrycka et al., 2022) and are more likely to immerse their heads and intentionally or accidentally swallow water (Sinclair, Jones, & Gerba, 2009). They are also likely to spend more time in shallow waters (Verhougstraete, Pogreba-Brown, Reynolds et al., 2020) or sand (Sanborn & Takaro, 2013) which demonstrate higher areas of contamination and greater health risk (Ferguson, Del Donno, Obeng-Gyasi et al., 2019; Sanborn & Takaro, 2013). For example, DeFlorio-Barker, Arnold, Sams et al. (2018) found in research with a combined inclusion of over 68,000 participants in the marine locations in the US that 76% of children between the age-group of 4-7 years were identified to engage in sand digging activities while visiting beaches compared to 22% of adults 35 years or older.

The skill level of the individual engaging in aquatic recreational activities has also been expressed as an important determinant in examining particularly involuntary water ingestion (WHO, 2021). From this standpoint, it is argued that those with novice or lower-level aquatic recreational skill levels are more likely to ingest greater volume of water more often due to reduced skill competency and relative inexperience.

Children may also be less likely than adults to “heed rules” and warning signage regarding hazardous water quality, which may unwittingly lead to increased exposure risk (WHO, 2021). A failure in basic hygiene practices, whereby children may be less likely to wash after swimming or to wash their hands between swimming and eating increase the chances of potential hand to mouth contamination.

This increased infection risk observed through a behavioural perspective may also be supported from a review of the literature conducted by Prüss (1998) who found that symptom rates were higher in younger age groups, and that studies on recreational water quality against assigned benchmark standards may therefore systematically underestimate risks to children (Leonard, Singer, Ukoumunne et al., 2018; World Health Organization, 2021) which consequently generates a greater overall health burden.

20.4 Exposure Assessment - Uncertainties and Limitations

Ingestion data for beach sand as an exposure medium in both adults and children is limited within the published literature. The current Australian guidelines for assessing human health risks from environmental hazards (EnHealth, 2012) does not provide data outlining specifications for beach sand. As international data on the ingestion of soil per day outdoors for adults is supplied, this information is substituted for the absent beach sand data. Mean data from international studies suggest a variating in daily ingested soil volumes ranging from 20-60mg/day however, for the purpose of this risk assessment 50mg/day was selected as the representative amount for beach sand ingestion. This may be seen to overestimate the total volume of ingested beach sand while engaging in typical adult recreational beach activities during an average beach visit suggested by Surf Life Saving Australia (2021) as 2.1 hours.

Ingestion rates for swimming activities provided by Dufour, A., Evans, O., Behymer, T. et al. (2006) for adults was 25 mL/hour, and this was the total ingestion estimate volume included in the current risk assessment. However, the above-mentioned study was conducted in a swimming pool rather than marine waters for primary contact aquatic activities. While this study is a common reference for ingestion values for recreational water there may present some misrepresentations when applied to the current study. Ingestion rates may differ from the controlled environmental conditions observed within a swimming pool to that observed within the natural elements experienced within a marine environment. Ingestion rates may not be representative of activities such as wading which is a common activity contacted in at the beach rather than a swimming pool, rather the ingestion volume recommended by Dufour and colleagues may be seen as an extreme value rather than as an actual representation.

21.0 Risk Characterisation

The four reference pathogens are used to investigate the risk of GI infection and illness from exposure to diffuse sources of domestic faecal contamination. These include exposures encountered through ingestion via the faecal oral route, as a result of beach water and beach sand exposure. The risk of infection as calculated through the application of the EM and EBMP is an important feature in determining risk in relation to exposure however, infection does not necessarily equate to illness.

The probability of annual infection and the probability of illness were also calculated for each pathogen in relation to faecal exposure to sewage, horse and dog excrement. The following equation as outlined by Haas, Rose, and Gerba (2014) was adopted.

$$\mathbf{P_{inf\ annual} = 1 - [1 - P_{inf,day}]^{n},} \qquad \text{Equation (3)}$$

Where the annual probability of infection is the probability of infection per day ($P_{inf,day}$) is calculated through either Equation (1) or Equation (2) and n is the number of exposure days per year (calculated as 2.5 beach visits per month (SLSA, 2021) x 4 month swim season).

The probability of illness was calculated as from Equation (4). The following equation devised by Hass and colleagues was used in the calculation of illness probability per single daily exposure (Haas, Rose, & Gerba, 2014).

$$\mathbf{P_{ill} = P_{infannual} \times P_{ill/inf}} \qquad \text{Equation (4)}$$

Where the probability of illness is the probability of annual infection ($P_{infannual}$) which is derived from Equation (3) and $P_{inf/ill}$, is a constant taken from the literature as the probability of illness per infection (Refer to table 10).

Table 11. List of values in converting P_{inf} to P_{ill}

Pathogen	**$P_{(inf/ill)}$**	**Reference**
Cryptosporidium	0.7	(World Health Organization, 2011)
Giardia	0.40	(Nash, Herrington, Losonsky et al., 1987)
Campylobacter	1.0	(Health Canada, 2019)
Salmonella	1.0	(USEPA, 2010)

Within this risk assessment three measures will be reported relating to GI health as the primary health outcome as a direct exposure to beach sand and marine waters for a single adult. The first of these relate to the risk of GI infection after a single exposure, the second relates to the risk of GI illness after a single exposure and the final observation relates to the risk of GI illness from annual (seasonal) exposures. A summary of each has been included in the following tables in addition with graphical displays which portray visible representations for each of the measured GI health outcomes. Each graph will also contain three colour shaded areas identified as red, amber and green which will correspond to the current GI risk classifications aligned with the Australian recreational water guidelines. The red shaded area corresponds to a GI illness risk of >10%, the amber shaded section represents between 1-10% and the green area indicated on each graph represents <1% risk of GI illness from the nominated exposure occurrence.

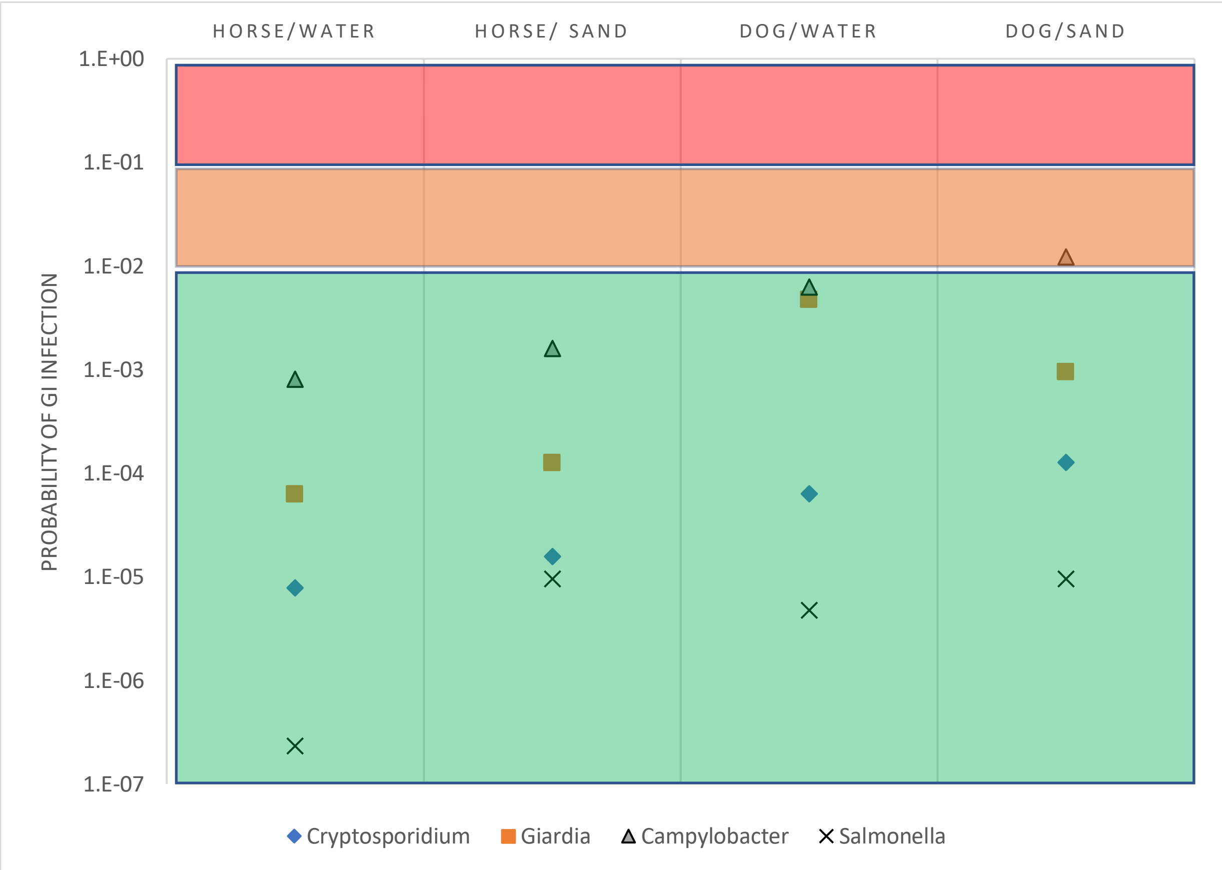
An assessment in determination of potential health risk levels after a single exposure for beachgoers to either beach sand or marine water with a hypothetical measure of enterococci at 200/100 CFU/mL of horse and dog faeces was applied to each scenario. In general, contamination as measured through each of the four reference pathogens within horse and dog faecal waste demonstrated an overall low risk level to human health from ingestion via marine water or beach sand (refer to Table 11 for a summary of measured risk of infection outcomes).

Table 12. GI Infection Risk for Adult Beachgoers After a Single Exposure (Results Summary)

	Horse/water	**Horse/ Sand**	**Dog/Water**	**Dog/Sand**
Cryptosporidium	7.89E-06	1.58E-05	6.37E-05	1.27E-04
Giardia	6.24E-05	1.25E-04	4.75E-03	9.51E-04
Campylobacter	8.06E-04	1.61E-03	6.26E-03	1.22E-02
Salmonella	2.33E-07	9.56E-06	4.79E-06	9.59E-06

In relation to reference pathogens, salmonella presence in sand and water for both animal species presented the lowest level of health risk to humans after a single exposure. This represents that for all variables except Dog/Sand-*Campylobacter* a risk of infection after a single exposure for adult beachgoers is measured as <1%, which is within the accepted levels for GI illness under the current NHMRC Australian recreational water guidelines. This is represented as the green section of the graph in Figure 5. The risk of infection outcomes formulated from the risk assessment process found that the Dog/Sand-*Campylobacter* variable demonstrated a corresponding level of risk of approximately 1.22%. This marginally exceeds the previous classification of <1%, therefore falling within the level of illness classification relating to an illness risk of between 1-5%, or an illness incidence of between 1 in 100 and 1 in 20 per exposure. This is represented within the amber section of the graph in Figure 5. In each of these cases assuming that all infections translate to illness, the Dog/Sand-*campylobacter* variable has a slightly higher level of risk than all other variables however, the risk is still within the accepted GI illness risk parameters for swimming exposure under the Australian recreational water guidelines.

Figure 5. Graphical Representation for Risk of GI Infection for Adult Exposures to Reference Enteric Pathogens



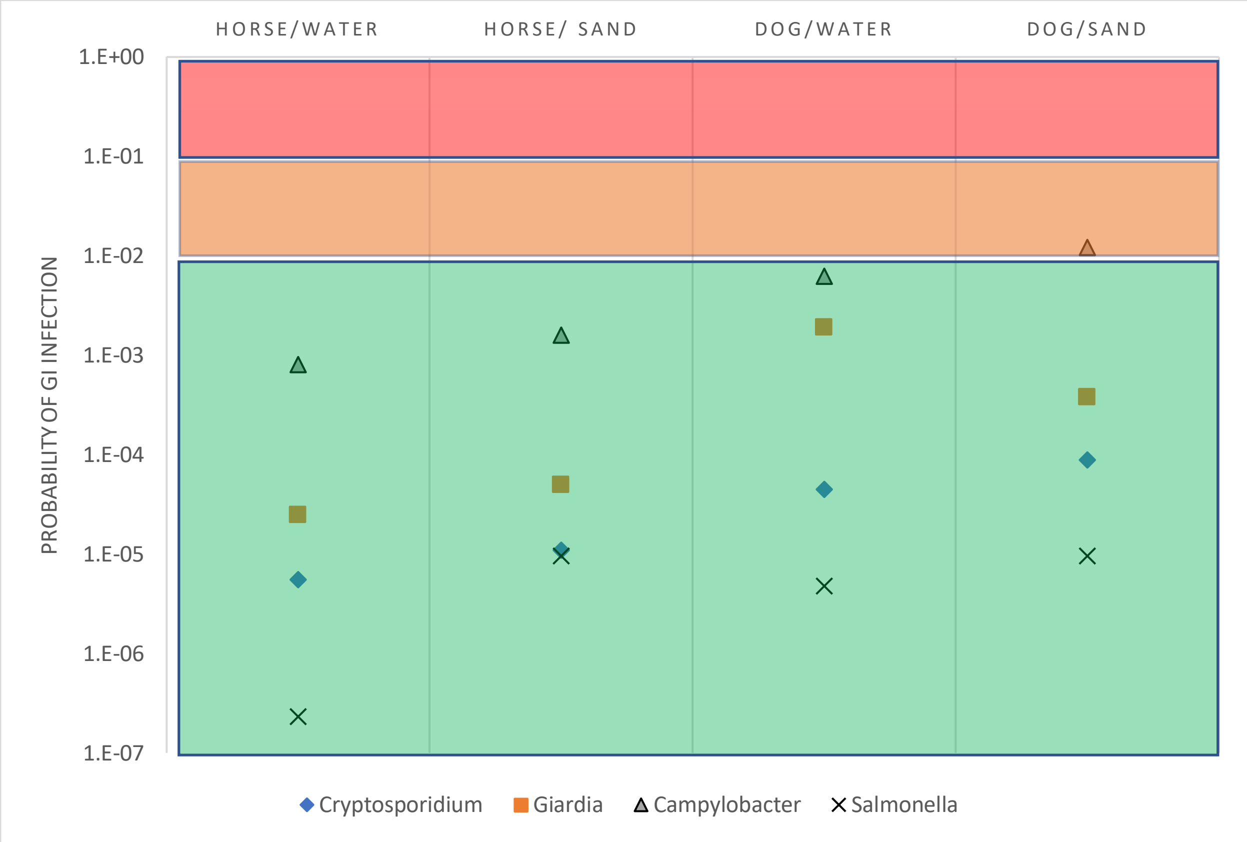
The second health measure undertaken within this risk assessment relates to the risk of illness for an adult beachgoer, after a single exposure. An assessment in determination of potential risk levels after a single exposure for adult beachgoers to either sand or water with a hypothetical measure of enterococci at 200/100 CFU/mL for horse and dog faeces contamination demonstrated an overall low risk to human health. A summary of findings is presented in Table 12. Each of the reference pathogens including *Cryptosporidium, Giardia and Salmonella* for both water and sand exposure for each animal species demonstrated a low-level health risk outcome. This related to a risk of GI illness of <1% which is illustrated in Figure 6 as the area highlighted in green.

Table 13. GI Illness Risk for Adult Beachgoers After a Single Exposure (Results Summary)

	Horse/water	**Horse/ Sand**	**Dog/Water**	**Dog/Sand**
Cryptosporidium	5.52E-06	1.10E-05	4.46E-05	8.92E-05
Giardia	2.50E-05	4.99E-05	1.90E-03	3.80E-04
Campylobacter	8.06E-04	1.61E-03	6.26E-03	1.22E-02
Salmonella	2.33E-07	9.56E-06	4.79E-06	9.59E-06

In relation to the reference pathogen *Campylobacter,* Horse/Water, Horse/Sand and Dog/Water also displayed a risk of GI illness from a single exposure of <1%. For the reference pathogen *Cam*pylobacter specific to the Dog/Sand variable measures at an illness risk level of >1% were observed. This represents a GI illness risk from a single exposure of between 1-5% as outlined within the NHMRC recreational water guidelines relating to microbial water quality. This is indicated in Figure 6 within the amber region of the associated graph. While beach sand is not currently supported with microbial assessment criteria within the NHMRC guidelines water quality markers have been supplemented as proxy set points in which to gauge an associate level of health risk.

Figure 6. Risk of GI Illness after a Single Exposure to Reference Pathogens from Enteric Contamination of Marine Water and Beach Sand.



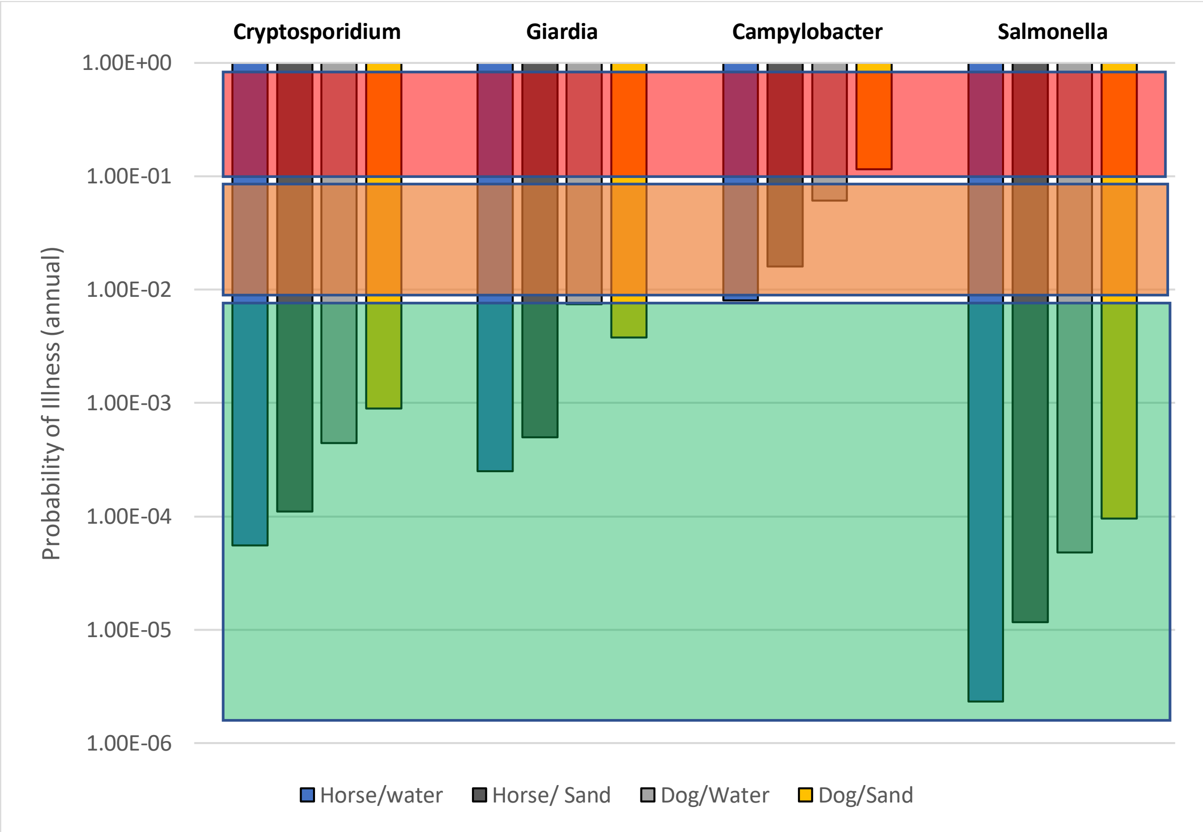
The final area of investigation in relation to this current risk assessment looks to examine the risk of illness for the nominated level of exposure during the course of the summer bathing season in Perth. This differed from the previous two health outcome assessments which investigated single or one-off exposures whereby the current assessment examined an accumulated health risk over a number of single exposures. An estimate of 10 seasonal beach visits by Surf Life Saving Australia (2021) for individuals within Western Australia was used to represent the total number of exposures. This was input into Equation 3 to generate an annual risk of infection whereby the outcome figure was input into Equation 4 which calculated the subsequent illness risk for the (annual) summer bathing season per individual. This exercise was repeated for each of the exposure variables, a summary of the associated risk levels is provided in Table 13.

Table 14. GI Illness Risk for Adult Beachgoers After Annual Exposure (Results Summary)

	Horse/water	Horse/ Sand	Dog/Water	Dog/Sand
Cryptosporidium	5.52E-05	1.10E-04	4.46E-04	8.92E-04
Giardia	2.50E-04	4.99E-04	7.45E-03	3.79E-03
Campylobacter	8.04E-03	1.60E-02	6.09E-02	1.16E-01
Salmonella	2.33E-06	1.17E-05	4.79E-05	9.59E-05

An assessment of accumulated GI illness risk across ten (10) individual recreational marine water and beach sand exposures to enterococci levels measured at 200/100 CFU/mL was conducted for each of the reference pathogens against each of the source variables. Outcomes of this risk assessment relating to the reference pathogens *Cryptosporidium, Giardia and Salmonella* demonstrated low level GI illness risks, which were demonstrated as <1%, or less than 1 illness incident for 100 exposures. This is represented as the green coloured area of the graph shown in Figure 7. The reference pathogen *Campylobacter,* has presented a greater potential risk of GI illness than each of the other reference pathogens. For this pathogen the assessed GI illness risk measured against the Horse/Sand and Dog/Water variables was shown to sit within the 1-5%, as illustrated within the NHMRC recreational water guidelines. This relates to an illness incidence of between 1 in 100 and 1 in 20 exposures. This shows a marginal increase in health risk compared to the other reference pathogens but is still maintained within an acceptable level of health risk defined within the guidelines. This is illustrated within the Figure 7 graph as the amber section. The assessed level of GI illness risk for the campylobacter pathogen relating to the Dog/Sand variable demonstrated the greatest level of potential risk to adult beachgoers upon exposure. This is represented in the graph contained within Figure 7 as the red coloured area. This level of assessed risk relates to a level of GI illness between 5-10%, or as a level of illness between 1 in 20 and 1 in 10 exposures.

Figure 7. Accumulated GI Risk of Illness



Reference pathogens were measured for both canine and equine species for faecal contamination of both marine water and beach sand. Findings for each were then compared with current NHMRC Australian recreational water guidelines whereby a risk level was determined. In examining the risk of infection for adult beachgoers after a single exposure to either water or sand in relation to the nominated reference enteric pathogens, it was found that the majority of risk exposures fell within the current allowable levels within the NHMRC guidelines. These levels are determined by the allowable levels of GI risk of illness for primary contact water based recreational activities as prescribed within the guidelines as shown previously in Part 1, Table 1.

While no comparable studies could be sourced which were conducted using similar measure variables as with this current risk assessment, a limited number of international studies may provide some reference value. From a search of the literature two studies conducted in the US over a decade ago demonstrated some areas of resemblance with this current risk assessment, however vast differences were also evident. The primary conclusions drawn from Soller, Schoen, Bartrand et al.

(2010) were that exposure to marine waters contaminated with fresh cattle faeces were comparable with those observed from human sources. While exposures experienced from direct fresh gull, chicken and pig faecal waste found to contaminate recreational marine waters demonstrated a significantly lower risk level of at least two orders of magnitude below that from human sources. Freshwater studies conducted by USEPA (2010) into manure contamination indirectly deposited into recreational waterways through runoff from rain events, found that the health risk would be at least an order of magnitude lower for waters impacted by a comparable level of manure runoff, compared to that from human wastewater origins.

In a comparative study investigating the health risk from enterococci exposure (35 CFU/100mL^{-1}) within recreational marine water contaminated with human wastewater and fresh gull faeces, Schoen and Ashbolt (2010) found the risk to swimmers was reduced in waters contaminated by gulls than that contaminated with sewage. Soller, Schoen, Varghese et al. (2014) also explored mixed enterococci contamination in recreational waters from human, chicken, pig and gull sources demonstrated a lower potential health risk from those waters containing higher proportions of animal rather than human waste material.

21.1 Risk Characterisation - Uncertainties and Limitations

It is acknowledged that not all infections translated into illness, which was assumed within the probability for illness ratios applied for campylobacter and salmonella. This conservative approach was applied through the inclusion of an infection-illness ratio of 1, meaning that for each reference pathogen individual infection would also result in illness. While this approach is a commonly accepted and applied practice within QMRA studies due to limited available conversion ratios, an overestimation of illness rates may also exist (McBride, Salmond, Bandaranayake et al., 1998). Infection to illness ratios applied for both *Cryptosporidium* and *Giardia* are taken from those published within the literature, it is likely that they were calculated through feeding trials or outbreak cases relating to food contamination (Haas, Rose, & Gerba, 2014). While this may assist in providing foundational information within the risk assessment process, ratios may over or under represent the conversion value in the context of waterborne pathogens in an aquatic marine setting.

As there are currently no Australian guidelines or standards for faecal indicator levels in beach sand, current parameters were applied for that specific to recreational water. As no previous research regarding enteric pathogen levels and GI illness of exposed beachgoers in Australian conditions had been undertaken, this approach was used in applying a foundational guide to assessing public health risk. Consequently, it is acknowledged that a degree of variability potentially exists in the life-cycle, virulence, dilution and abundance for each of the refence pathogens contained within the aquatic and beach sand environments and the impact this may have on infectivity and illness rates.

The values used within the National recreational water guidelines in classification of health risk were generated through research involving healthy adult recreational aquatic participants swimming in sewage-impacted marine waters (WHO, 2021). As these guidelines were used as the health measure within the current risk assessment for exposure to faecal contamination from domestic dog and horse excrement in both marine water and beach sand, some inconsistencies may be evident in the overall health outcomes.

22.0 Recommendations

1. Revise and update the NHMRC recreational water guidelines to include specific microbial indicator parameters in the assessment of human health risks associated with beach sand exposure.

2. Implement measures to incorporate beach sand analysis into the existing cycle of routine water analysis for all recreational marine settings currently monitored within state or local government jurisdictions.

3. Invest research efforts into better understanding the potential GI health impacts of beach sand exposure contaminated with enteric pathogens across a variety of diverse user groups and recreational activities.

4. Local government authorities to erect visible signage at high-risk recreational marine locations notifying pet owner to remove faecal material deposited by their pets while at the beach.

5. Develop and expand upon the current knowledge-base relating to diffuse contamination from domestic animal sources on both beach sand and marine recreational waters from both a national and international perspective.

23.0 Conclusion

A desktop case study implementing a real-world example was used in assessing the human health risks in relation to animal faecal pathogen exposures for beachgoers at a recreational marine environment. Recreational exposure scenarios were constructed involving both marine water and beach sand, in examining the GI health risk associated with reference pathogens typically found within the faeces of domestic canine and equine species. A review of the current literature found no evidence of a similar study conducted previously either nationally or internationally. This investigation incorporating the variables of marine water and beach sand, in addition with the enteric pathogens from horse and dog excrement, has attempted to address an important gap in the public health literature.

Enteric waterborne bacteria and protozoa were chosen as reference pathogens and used in assessing the risk of GI infection and illness in adults upon incidental exposure, while engaging in recreational beach activities. Ingestion, through the faecal oral route of exposure was the selected pathway used in the study, as these were common processes identified within the literature leading towards the health outcome under investigation. Outcome health measures for both pathogen contamination of water and sand exposure were assessed in relation to GI infection after a single exposure, GI illness after a single exposure and GI illness after multiple (seasonal) exposures. Exposure risk for each of the four reference pathogens was recorded and measured against the current NHMRC recreational water guidelines in order to gauge an overall GI risk status. Campylobacter from dog faeces deposited in beach sand provided the greatest health risk for GI health outcomes upon exposure to adults engaging in land based recreational activities at the beach within this study.

Findings from this study, including implementing microbial assessments of both water and beach sand for marine environments into the NHMRC guidelines, were also presented as recommendations in order to guide future research and public health practices.

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APPENDICES

Appendix 1. Articles selected for review based on inclusion and exclusion status with reasons

Number	Reference	Inclusion (I)/ Exclusion (E)	Reason for Exclusion
1	Abbott, B., Lugg, R., Devine, B., Cook, A., & Weinstein, P. (2011). Microbial risk classifications for recreational waters and applications to the Swan and Canning Rivers in Western Australia. *Journal of Water and Health*, *9*(1), 70-79. doi:10.2166/wh.2011.016	E	Does not measure recreational water exposure
2	Abdelzaher, A. M., Wright, M. E., Ortega, C., Hasan, A. R., Shibata, T., Solo-Gabriele, H. M., Kish, J., Withum, K., He, G., Elmir, S. M., Bonilla, J. A., Bonilla, T. D., Palmer, C. J., Scott, T. M., Lukasik, J., Harwood, V. J., McQuaig, S., Sinigalliano, C. D., Gidley, M. L., Wanless, D., Plano, L. W., Garza, A. C., Zhu. X., Stewart, J. R., Dickerson, J. W., Yampara-Iguise, H., Carson, C., Feisher, J. M., & Fleming, L. E. (2011). Daily measures of microbes and human health at a non-point source marine beach. *Journal of water and health*, 9(3), 443–457. doi.org/10.2166/wh.2011.146	E	The study has a focus on international (US) beaches rather than Australian natural recreational water bodies.
3	Ahmed, W., Hamilton, K., Toze, S., Cook, S., & Page, D. (2019). A review on microbial contaminants in stormwater runoff and outfalls: Potential health risks and mitigation strategies. *Science of The Total Environment*, *692*, 1304-1321. doi:10.1016/j.scitotenv.2019.07.055	E	This paper summarizes occurrence and concentrations of faecal indicators, pathogens, and MST marker genes in urban stormwater. There is no consideration of recreational water therefore the article was excluded.
4	Ashbolt, N. J., & Bruno, M. (2003). Application and refinement of the WHO risk framework for recreational waters in Sydney, Australia. *Journal of Water and Health*, *1*(3), 125-131.	E	Recreational exposure was not considered.
5	Ashbolt, N. J., Schoen, M. E., Soller, J. A., & Rose, D. J. (2010). Predicting pathogen risks to aid beach management: The real value of	E	Based on QMRA modelling

	quantitative microbial risk assessment (QMRA). *Water Research, 44*(16), 4692-4703. doi:10.1016/j.watres.2010.06.048		
6	Backer, L. C., Carmichael, W., Kirkpatrick, B., Williams, C., Irvin, M., Zhou, Y., Johnson, T. B., Nierenberg, K., Hill, V. R., Kieszak, S. M., & Cheng, Y. S. (2008). Recreational exposure to low concentrations of microcystins during an algal bloom in a small lake. *Marine Drugs*, 6(2), 389–406. https://doi.org/10.3390/md20080018	E	Study conducted overseas (US)
7	Bernard, A. G. (1989). The bacteriological quality of tidal bathing waters in Sydney (Australia). *Water Science and Technology, 21*(2), 65-69. doi:10.2166/wst.1989.0029	E	Study focused on contamination sampling and did not explore human exposure.
8	Butler, T., & Ferson, M. J. (1997). Faecal pollution of ocean swimming pools and stormwater outlets in eastern Sydney. *21*(6), 567-571. doi:https://doi.org/10.1111/j.1467-842X.1997.tb01756.x	E	Individual exposure was not measured, and health symptoms were not recorded. Potential health risks were noted with ocean pools as with that found in surrounding beaches.
9	Carney, R. L., Brown, M. V., Siboni, N., Raina, J. B., Kahlke, T., Mitrovic, S. M., & Seymour, J. R. (2020). Highly heterogeneous temporal dynamics in the abundance and diversity of the emerging pathogens Arcobacter at an urban beach. *Water Research, 171*. doi:10.1016/j.watres.2019.115405	E	Did not explore human recreational exposure.
10	Chamberlain, M., Marshall, A. N., & Keeler, S. (2019). Open Water Swimming: Medical and Water Quality Considerations. *Current Sports Medicine Reports, 18*(4), 121-128. doi:10.1249/JSR.0000000000000582	E	There were no measures of human exposure.
11	Choong, K. Y., & Roberts, L. J. (1999). Molluscum contagiosum, swimming and bathing: a clinical analysis. *The Australasian Journal of Dermatology*, 40(2), 89–92. https://doi.org/10.1046/j.1440-0960.1999.00327.x	E	Recreational water analysis was not conducted.

12	Chorus, I., Falconer, I. R., Salas, H. J., & Bartram, J. (2000). Health risks caused by freshwater cyanobacteria in recreational waters. *Journal Of Toxicology and Environmental Health-Part B-Critical Reviews, 3*(4), 323-347. doi:10.1080/109374000436364	E	Does not measure recreational exposure.
13	Corbett, S. J., Rubin, G. L., Curry, G. K., & Kleinbaum, D. G. (1993). The health effects of swimming at Sydney beaches. The Sydney Beach Users Study Advisory Group. *American journal of public health, 83*(12), 1701-1706. doi:10.2105/ajph.83.12.1701	I	Included
14	Crase, L., & Gillespie, R. (2008). The impact of water quality and water level on the recreation values of Lake Hume. *Australasian Journal of Environmental Management, 15*(1), 21-29. doi:10.1080/14486563.2008.9725179	E	No measures of human recreational water exposure.
15	Crawford, A., Holliday, J., Merrick, C., Brayan, J., van Asten, M., & Bowling, L. (2017). Use of three monitoring approaches to manage a major Chrysosporum ovalisporum bloom in the Murray River, Australia, 2016. *Environmental Monitoring and Assessment, 189*(4). doi:10.1007/s10661-017-5916-4	E	No measures of human recreational water exposure.
16	Cristiane Pinto, K., de Souza Lauretto, M., Navarro Gonzaléz, M. I. J., Sato, M. I. Z., Nardocci, A. C., & Razzolini, M. T. P. (2020). Assessment of health risks from recreational exposure to Giardia and Cryptosporidium in coastal bathing waters. *Environmental Science and Pollution Research, 27*(18), 23129-23140. doi:10.1007/s11356-020-08650-2	E	Overseas study (Brazil)
17	Dale, K., Kirk, M., Sinclair, M., Hall, R., & Leder, K. (2010). Reported waterborne outbreaks of gastrointestinal disease in Australia are predominantly associated with recreational exposure. *Australian and New Zealand journal of public health, 34*(5), 527-530. doi:10.1111/j.1753-6405.2010.00602.x	E	Reporting focuses on swimming pools

18	Dale, K., Wolfe, R., Sinclair, M., Hellard, M., & Leder, K. (2009). Sporadic gastroenteritis and recreational swimming in a longitudinal community cohort study in Melbourne, Australia. *American Journal of Epidemiology, 170*(12), 1469-1477. doi:10.1093/aje/kwp297	E	No water analysis conducted.
19	Daly, E., Kolotelo, P., Schang, C., Osborne, C. A., Coleman, R., Deletic, A., & McCarthy, D. T. (2013). Escherichia coli concentrations and loads in an urbanised catchment: The Yarra River, Australia. *Journal of Hydrology, 497*, 51-61. doi:10.1016/j.jhydrol.2013.05.024	E	Not focused on recreational water
20	Dorevitch, S., DeFlorio-Barker, S., Jones, R. M., & Liu, L. (2015). Water quality as a predictor of gastrointestinal illness following incidental contact water recreation. *Water Research, 83*, 94-103. doi:https://doi.org/10.1016/j.watres.2015.06.028	E	Study conducted overseas (US).
21	Falconer, I. R. (1996). Potential impact on human health of toxic cyanobacteria. *Phycologia., 35*(SUPPL.), 6-11. doi:10.2216/i0031-8884-35-6s-6.1	E	Does not measure recreational water exposure
22	Falconer, I. R. (1999). An overview of problems caused by toxic blue-green algae (cyanobacteria) in drinking and recreational water. *Environmental Toxicology, 14*(1), 5-12. doi:10.1002/(sici)1522-7278(199902)14:1<5::Aid-tox3>3.0.Co;2-0		No assessment of human recreational exposure
23	Falconer, I. R. (2001). Toxic cyanobacterial bloom problems in Australian waters: risks and impacts on human health. *Phycologia, 40*(3), 228-233. doi:10.2216/i0031-8884-40-3-228.1	E	No analysis of recreational water
24	Fleisher, J. M., Fleming, L. E., Solo-Gabriele, H. M., Kish, J. K., Sinigalliano, C. D., Plano, L., Elmir, S. M., Wang, J. D., Withum, K., Shibata, T., Gidley, M. L., Abdelzaher, A., He, G., Ortega, C., Zhu, X., Wright, M., Hollenbeck, J., & Backer, L. C. (2010). The BEACHES Study: health effects and exposures from non-point source microbial contaminants in subtropical recreational marine waters. *International*	E	Study conducted overseas (US).

	Journal of Epidemiology, 39(5), 1291–1298. https://doi.org/10.1093/ije/dyq084		
25	Gibney, K. B., O'Toole, J., Sinclair, M., & Leder, K. (2017). Burden of Disease Attributed to Waterborne Transmission of Selected Enteric Pathogens, Australia, 2010. *American Journal of Tropical Medicine and Hygiene*, *96*(6), 1400-1403. doi:10.4269/ajtmh.16-0907	E	Study conducted overseas (US).
26	Gitter, A., Mena, K. D., Wagner, K. L., Boellstorff, D. E., Borel, K. E., Gregory, L. F., & Karthikeyan, R. (2020). Human Health Risks Associated with Recreational Waters: Preliminary Approach of Integrating Quantitative Microbial Risk Assessment with Microbial Source Tracking. *12*(2), 327.	E	Focused on quantitative microbial risk assessment (QMRA) modelling of human health risks associated with recreational water.
27	Greenwood, K. P., & Reid, S. A. (2020). Clustering of cryptosporidiosis in Queensland, Australia, is not defined temporally or by spatial diversity. *International Journal for Parasitology*, *50*(3), 209-216. doi:10.1016/j.ijpara.2019.11.010	E	Not based on recreational water
28	Hamilton, K. A., Waso, M., Reyneke, B., Saeidi, N., Levine, A., Lalancette, C., & Ahmed, W. (2018). Cryptosporidium and Giardia in Wastewater and Surface Water Environments. *Journal of Environmental Quality JEQ.*, *47*(5), 1006-1023. doi:10.2134/jeq2018.04.0132	E	Not recreational water focused
29	Harrington, J. F., Wilcox, D. N., Giles, P. S., Ashbolt, N. J., Evans, J. C., & Kirton, H. C. (1993). the health of Sydney surfers - an epidemiologic study. *Water Science and Technology*, *27*(3-4), 175-181. doi:10.2166/wst.1993.0342	I	Included
30	Hart, J., Mooney, L., Arthur, I., Inglis, T. J. J., & Murray, R. (2014). First case of Chlorella wound infection in a human in Australia. *New Microbes and New Infections*, *2*(4), 132-133. doi:10.1002/nmi2.50	E	Case study- no recreational water analysis.

31	Hess, I., Hickey, C., & Bowling, L. (2008). Bug Breakfast in the Bulletin. Recreational water: surfing the bugs. *New South Wales public health bulletin, 19*(5-6), 108-109. doi:10.1071/nb08006	E	commentary
32	Hose, G. C., Murray, B. R., Gordon, G., McCullough, F. E., & Pulver, N. (2005). Spatial and rainfall related patterns of bacterial contamination in Sydney Harbour estuary. *Journal of Water and Health, 3*(4), 349-358. doi:http://dx.doi.org/10.2166/wh.2005.060	E	Deals primarily with modelling
33	Hughes, B., Beale, D. J., Dennis, P. G., Cook, S., & Ahmed, W. (2017). Cross-Comparison of Human Wastewater-Associated Molecular Markers in Relation to Fecal Indicator Bacteria and Enteric Viruses in Recreational Beach Waters. *Applied and Environmental Microbiology, 83*(8). doi:10.1128/aem.00028	E	Microbial source tracking markers
34	Kueh, C. S. W., & Grohmann, G. S. (1989). Recovery of viruses and bacteria in waters off Bondi beach: A pilot study. *Medical Journal of Australia, 151*(11-12), 632-638. doi:10.5694/j.1326-5377.1989.tb139636.x	E	Does not measure recreational exposure.
35	Lepesteur, M., McComb, A. J., & Moore, S. A. (2006). Do we all face the same risk when bathing in the estuary? *Water Research, 40*(14), 2787-2795. doi:10.1016/j.watres.2006.04.025	I	Included
36	Lepesteur, M., Wegner, A., Moore, S. A., & McComb, A. (2008). Importance of public information and perception for managing recreational activities in the Peel-Harvey estuary, Western Australia. *Journal of Environmental Management, 87*(3), 389-395. doi:10.1016/j.jenvman.2007.01.026	E	No investigation of health symptoms or outcomes.
37	Lévesque, B., Gervais, M. C., Chevalier, P., Gauvin, D., Anassour-Laouan-Sidi, E., Gingras, S., Fortin, N., Brisson, G., Greer, C., & Bird, D. (2014). Prospective study of acute health effects in relation to	E	This is an international study (Canada)

	exposure to cyanobacteria. *The Science of the Total Environment*, *466-467*, 397–403. https://doi.org/10.1016/j.scitotenv.2013.07.045		
38	Loganthan, S., Yang, R. C., Bath, A., Gordon, C., & Ryan, U. (2012). Prevalence of Cryptosporidium species in recreational versus non-recreational water sources. *Experimental Parasitology, 131*(4), 399-403. doi:10.1016/j.exppara.2012.04.015	E	Does not measure recreational exposure.
39	Manning, S. S., Dixon, J. P., Birch, G. F., & Besley, C. H. (2019). Deepwater ocean outfalls: A sustainable solution for sewage discharge for mega-coastal cities (Sydney, Australia): Influences on beach water quality. *Marine Pollution Bulletin, 145*, 691-706. doi:10.1016/j.marpolbul.2019.05.010	E	Does not measure recreational exposure.
40	Masters, N. M., Wiegand, A., Thompson, J. M., Vollmerhausen, T. L., Hatje, E., & Katouli, M. (2017). Enterococci populations of a metropolitan river after an extreme flood event: prevalence, persistence and virulence determinants. *Journal of Water and Health, 15*(5), 684-694. doi:10.2166/wh.2017.284	E	Not exclusive to recreational waters/
41	McGregor, G. B., Stewart, I., Sendall, B. C., Sadler, R., Reardon, K., Carter, S., & Wickramasinghe, W. (2012). First Report of a Toxic Nodularia spumigena (Nostocales/Cyanobacteria) Bloom in Sub-Tropical Australia. I. Phycological and Public Health Investigations. *International Journal of Environmental Research and Public Health, 9*(7), 2396-2411. doi:10.3390/ijerph9072396	E	Explores aquatic microbial tracking technologies.
42	Napier, M. D., Haugland, R., Poole, C., Dufour, A. P., Stewart, J. R., Weber, D. J., Varma, M., Lavender, J. S., & Wade, T. J. (2017). Exposure to human-associated fecal indicators and self-reported illness among swimmers at recreational beaches: a cohort study. *Environmental Health: a global access science source*, *16*(1), 103. https://doi.org/10.1186/s12940-017-0308-3	E	International study focusing on the US.

43	Osborne, N. J., & Shaw, G. R. (2008). Dermatitis associated with exposure to a marine cyanobacterium during recreational water exposure. *BMC Dermatology*, *8*(1), 5. doi:10.1186/1471-5945-8-5	E	Cases were taken from first aid records. There were no comparator groups identified, water analysis was not undertaken and exposure status was limited or missing.
44	Osborne, N. J., Shaw, G. R., & Webb, P. M. (2007). Health effects of recreational exposure to Moreton Bay, Australia waters during a Lyngbya majuscula bloom. *Environment International*, *33*(3), 309-314. doi:10.1016/j.envint.2006.10.011	E	The study relies on anecdotal evidence for local community members of algal blooms. Daily bloom measurements were not taken to due logical and financial barriers.
45	Pilotto, L. S., Douglas, R. M., Burch, M. D., Cameron, S., Beers, M., Rouch, G. J., & Attewell, R. G. (1997). Health effects of exposure to cyanobacteria (blue-green algae) during recreational water-related activities. *Australian and New Zealand Journal of Public Health*, *21*(6), 562-566. doi:10.1111/j.1467-842X.1997.tb01755.x	I	Included
46	Schang, C., Henry, R., Kolotelo, P. A., Prosser, T., Crosbie, N., Grant, T., & McCarthy, D. T. (2016). Evaluation of Techniques for Measuring Microbial Hazards in Bathing Waters: A Comparative Study. *PloS One*, *11*(5). doi:10.1371/journal.pone.0155848	E	Explores aquatic microbial testing technologies specific to recreational water.
47	Schang, C., Lintern, A., Cook, P. L. M., Osborne, C., McKinley, A., Schmidt, J., & McCarthy, D. (2016). Presence and survival of culturable Campylobacter spp. and Escherichia coli in a temperate urban estuary. *Science of The Total Environment*, *569-570*, 1201-1211. doi:10.1016/j.scitotenv.2016.06.195	E	Does not explore recreational waters.
48	Siddiqee, M. H., Henry, R., Coleman, R. A., Deletic, A., & McCarthy, D. T. (2019). Campylobacter in an urban estuary: Public health insights from occurrence, hela cytotoxicity, and Caco-2 attachment cum invasion. *Microbes and Environments*, *34*(4), 436-445. doi:10.1264/jsme2.ME19088	E	Does not explore recreational waters.

49	Sidhu, J. P. S., Hodgers, L., Ahmed, W., Chong, M. N., & Toze, S. (2012). Prevalence of human pathogens and indicators in stormwater runoff in Brisbane, Australia. *Water Research, 46*(20), 6652-6660. doi:10.1016/j.watres.2012.03.012	E	Does not examine recreational exposure.
50	Stewart, I., Webb, P. M., Schluter, P. J., Fleming, L. E., Burns, J. W., Gantar, M., & Shaw, G. R. (2006). Epidemiology of recreational exposure to freshwater cyanobacteria - an international prospective cohort study. *BMC Public Health, 6*. doi:10.1186/1471-2458-6-93	I	This study while focusing on Australian cases also included a sample population from Florida (USA). This study has been included as 84% (n= 1,115) of those recruited for the study were from locations within Australia.
51	Teixeira, P., Salvador, D., Branda, J., Ahmed, W., Sadowsky, M. J., & Valerio, E. (2020). Environmental and Adaptive Changes Necessitate a Paradigm Shift for Indicators of Fecal Contamination. *Microbiology Spectrum, 8*(2). doi:10.1128/microbiolspec.ERV-0001-2019	E	Discusses surveillance and monitoring systems.
52	Tillett, B. J., Sharley, D., Almeida, M., Valenzuela, I., Hoffmann, A. A., & Pettigrove, V. (2018). A short work-flow to effectively source faecal pollution in recreational waters - A case study. *Science of The Total Environment, 644*, 1503-1510. doi:10.1016/j.scitotenv.2018.07.005	E	Presents a case study of faecal monitoring tools.
53	Veal, C. J., Neelamraju, C., Wolff, T., Watkinson, A., Shillito, D., & Canning, A. (2018). Managing cyanobacterial toxin risks to recreational users: a case study of inland lakes in South East Queensland. *Water Science and Technology-Water Supply, 18*(5), 1719-1726. doi:10.2166/ws.2017.233	E	Does not measure recreational water exposure.
54	Wohlsen, T., Bates, J., Gray, B., Aldridge, P., Stewart, S., Williams, M., & Katouli, M. (2006). The occurrence of Cryptosporidium and Giardia in the Lake Baroon catchment, Queensland, Australia. J*ournal of Water Supply Research and Technology-Aqua, 55*(5), 357-366. doi:10.2166/aqua.2006.044	E	Does not explore recreational water.