Skip all front matter: Jump to Page 1

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RAND EUROPE

The Health Risks of Bathing in Recreational Waters

A Rapid Evidence Assessment of Water Quality and Gastrointestinal Illness

Sarah King, Josephine Exley, Eleanor Winpenny, Lottie Alves, Marie-Louise Henham, Jody Larkin

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Prepared for DEFRA

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Preface

The European Bathing Waters Directive (2006/7/EC) stipulates water quality classification standards for recreational bathing waters. It was revised in 2006 based on evidence reviewed in 2003. The Department for Environment, Food & Rural Affairs (Defra) commissioned RAND Europe, supported by topic experts David Kay (Centre for Research into Environment and Health, University of Aberystwyth) and Alan Lyne (Senior Consultant Microbiologist, ADAS UK Ltd), to conduct a rapid evidence assessment of studies published since 2003 that evaluate the relationship between recreational bathing waters and gastrointestinal illness. This report summarises the findings of the review corresponding to two research questions:

1. What is the post-2003 evidence for the health risks of recreational bathing in general – and to specific groups of bathers in particular?
2. What is the evidence to support the different classification standards outlined in the European Bathing Directive?

In addressing these questions this report provides a detailed summary and quality assessment of the latest evidence, and formulates research recommendations, intended to aid interested policy makers, researchers, government agencies, advocates, community groups and other stakeholders in the lead up to the planned 2020 review of the European Bathing Directive.

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Abstract

The 2006/7/EC European Bathing Directive stipulates water quality classification standards for recreational bathing waters based on specified limits for Faecal Indicator Organisms (FIOs). Presence of FIOs above the limits is considered to be indicative of poor water quality and to present a risk to bathers' health. The health risks most closely associated with bathing are faecal-oral diseases which cause gastrointestinal illnesses (GI) such as diarrhoea and vomiting.

The European Bathing Directive is due to be reviewed in 2020. Defra commissioned this rapid evidence assessment (REA) on recreational bathing waters and GI to identify the extent of the literature published since the previous review (the 2006/7 standards were based, in part, on World Health Organization (WHO) evidence published in 2003), and to determine whether there is any new evidence which may indicate whether or not a revision to the Directive would be justified.

We identified and extracted data from 21 relevant papers (from 16 studies) published since 2003; 12 were conducted in marine waters and four were conducted in freshwater. Considerable heterogeneity existed between study protocols and the majority had significant methodological limitations, including self-selection and misclassification biases. Moreover, there was limited variation in water quality between studies. In particular, few studies were conducted in 'poor' water quality, and none were conducted in 'sufficient' water, thus providing a limited evidence base in which to assess the classification standards.

Overall, there appeared to be a significant relationship between FIOs and GI in fresh water studies, but not in marine water studies. Given an apparent lack of a relationship between GI and water quality levels meeting different classification standards, it is unclear whether the 2006/7/EC Bathing Waters Directive classification standards are supported by studies published in the post 2003 period. More UK epidemiological evidence is needed to disprove or confirm the findings of the original studies that were used to derive the boundaries for marine waters.

Table of Contents

Figures

Tables

Summary

The quality standards in the current EU Bathing Waters Directive (2006/6/EC) are based, in part, on epidemiological research reviewed in 2003 by the World Health Organization, but they are due to be re-examined in 2020. This rapid evidence assessment sought to evaluate the current epidemiological literature that examines the relationship between recreational water use (i.e. exposure to marine water and freshwater recreational waters) and gastrointestinal illness (GI), and to highlight any significant new research and/or evidence gaps which may help inform future bathing water quality guidelines. Specifically, it focused on literature which presented water quality information based on the concentration of faecal indicator organisms (*E.coli* and enterococci) and gastrointestinal illness (GI) in order to answer the following research questions:

3. What is the post-2003 evidence for the health risks of recreational bathing in general – and to specific groups of bathers in particular?
4. What is the evidence to support the different classification standards outlined in the European Bathing Directive?

The methodology of the review followed a systematic review process, limited only by searching for studies published from 2003 onwards (hence it is termed a rapid evidence assessment rather than a full systematic review). At least two reviewers were involved in each stage of the review process, and a third reviewer checked any decisions, thus limiting the potential for reviewer error and bias.

Overall, 21 papers (from 16 studies), including two randomised controlled trials and 14 observational studies, met the inclusion criteria of our review. Twelve of these studies were conducted in marine waters (11 were conducted in Mediterranean type or subtropical climates and one in a coastal lagoon), and four were conducted in fresh waters (all in temperate climates). Thus, while it is likely that some of the results from the freshwater studies may be directly applicable to the UK, very few of the reported results for marine studies may be applicable to the temperate British climate.

1. What is the post 2003 evidence for the health risks of recreational bathing in general – and also to specific groups of bathers?

Based on studies included in our review, there is continuing evidence that bathing in recreational water poses some increased risk of GI to bathers compared with non-bathers. Most studies evaluated the risk of bathing in beachgoers of all age groups. Only two studies reported results separately by age group of bathers, and only one recent study investigated the risk of GI among other water users (e.g. in people canoeing, fishing, kayaking, motor boating, or rowing), so the data on these specific population groups remain limited. Interestingly, our review of studies published since 2003 found that:

- There appears to be little or no significant difference between GI in bathers compared with non-bathers at marine beaches.
- In contrast, there appears to be a consistent and significantly higher risk of GI in bathers compared with non-bathers in freshwater sites in temperate climates (up to 3.2 times higher).
- There is some evidence to suggest that increased bather exposure (i.e. head immersion or swallowing water) results in a higher risk of GI, particularly for freshwater bathers.
- There is evidence to suggest that an increase in time spent in water is associated with an increase in GI.
- There is very little evidence on how the risk of GI varies with age.
- There is a lack of recent studies which have evaluated the risk of GI in recreational water users other than bathers (e.g. in people canoeing, fishing, kayaking, motor boating, or rowing).

2. What is the evidence to support the different classification standards outlined in the European Bathing Directive?

It was possible to approximate the water quality in eight of the studies (six marine and two freshwater) against the European Bathing Directive classifications. For the six marine studies, the water quality in one study could be classified as 'poor' and in two as 'excellent' or 'good'. For the remaining three studies, the water quality varied. For the two freshwater studies, both could be classified as 'excellent'.

To evaluate current bathing indicator standards, this review considered studies which examined a dose response, i.e. a relationship between increasing numbers/density of faecal organisms in the water, either as a continuous measure or as a cut-off value, and increased risk of GI. We also considered studies that reported the risk of GI in waters with differing pollution levels. This evidence was required to investigate the relationship between the concentration of faecal indicator organisms (FIOs) in water and GI, and to infer whether or not the literature supports the European Bathing Directive (2006) boundaries. Our review of studies published from 2003 onwards found that:

- There is little evidence for a significant dose response between faecal indicator organisms and GI in marine water.
- There appears to be a significant dose response between faecal indicator organisms and GI in fresh water.
- Very high levels of pollution due to heavy rainfall and urban run-off or sewage contamination are associated with increased GI.

Overall, it is difficult to draw any firm conclusions from this evidence because of the heterogeneity of study protocols and methodological limitations, including self-selection and misclassification biases. Thus, the various results presented by the study authors could be an artefact of the range of methods used. Moreover, there was limited variation in water quality among studies. In particular, few studies were conducted in 'poor' quality water, and none were conducted in 'sufficient' quality water, thus providing a limited evidence base on which to assess the classification standards.

However, two methodologically robust studies (randomised controlled trials (RCT)) identified in our rapid evidence review were well conducted, and their results are likely to be reliable and worthy of mention. One study, conducted in 'poor' quality marine water in Florida, United States (semi-tropical climate), found that bathers were almost two times more likely to report an episode of GI following water exposure than non-bathers, although the results were not statistically significant. We note, however, that this study also evaluated other illnesses and that the authors concluded that bathers may be at a significantly increased risk of skin illnesses relative to non-bathers. The other randomised controlled trial was conducted in 'excellent' quality freshwater sites in Germany (temperate climate). This study found that the crude relative risk of GI was, significantly, more than two times greater in bathers compared with non-bathers. This increased to more than three and half times when bathers who were exposed to a (defined) higher level of enterococci concentration were compared with non-bathers.

With the methodological limitations of all of the included studies in mind, the following general conclusions may be made:

- Based on 16 studies published since 2003, there appears to be a consistent significant relationship between faecal indicator organisms (used to measure water quality) and GI in freshwater studies, but not in marine water studies.
- Given the apparent lack of relationship between GI and water quality levels meeting different boundaries, it is unclear whether the boundaries of the 2006/7/EC Bathing Waters Directive are supported by studies published in the post-2003 period.

We suggest that more UK epidemiological evidence is needed to disprove or confirm the findings of the original studies that were used to derive these boundaries for marine waters.

Acknowledgements

We would like to thank our expert advisors Professor David Kay (Director of the Centre for Research into Environment and Health, at the University of Aberystwyth) and Alan Lyne (Senior Consultant Microbiologist, ADAS UK Ltd) for their valuable input. They provided expertise on water quality and were involved in all aspects of the review process.

We would also like to thank the team at Defra and the Joint Water Evidence Group (JWEG) for their helpful suggestions. This team includes Elaine Connolly, Kate Hedges, Victor Aguilera, Deborah Coughlin, and Alexandra Collins.

Finally, we would like to thank our quality assurance reviewers, Molly Morgan Jones and Emma Pitchforth at RAND Europe, for their helpful insights.

Abbreviations

aR	Attributable Risk
aCIR	adjusted Cumulative Incidence Ratio
CE	Cell Equivalents
CFU	Colony Forming Unit
CI	Confidence Interval
Defra	Department for Environment, Food and Rural Affairs
EPA	US Environmental Protection Agency
FIB	Faecal Indicator Bacteria
FIO	Faecal Indicator Organism
GI	Gastrointestinal Illness
HCGI	Highly Credible Gastrointestinal Illness
MF	Membrane Filtration
NOAEL	No Observed Adverse Effect Limit
OR	Odds Ratio
qPCR	quantitative Polymerase Chain Reaction
RR	Relative Risk
SD	Standard Deviation
WHO	World Health Organisation

1. Introduction

1.1. Background

Across the European Union there are more than 20,000 designated bathing areas[1]; 14,494 coastal bathing waters and 6,436 inland bathing waters [1]. Throughout the designated bathing season in Europe, which runs from the end of May to the end of September, the water quality of these bathing waters is monitored to assess whether bathing sites comply with quality standards outlined in the European Bathing Waters Directive (2006/6/EC). The quality standards specify acceptable limits for certain types of bacteria in inland and, coastal and marine water. Presence of these bacteria above the limits is considered to be indicative of poor water quality and to present a risk to bathers' health [2].

The coastal and marine water quality standards in the current EU Bathing Waters Directive (2006/6/EC) were, in part, based on the World Health Organization's (WHO) Guidelines for Safe Recreational Water Environment published in 2003 [3], which in turn are based on two randomised control trials conducted in the UK [4-6]. The inland (freshwater) quality standards were based on the results of an unpublished randomised control trial conducted in Germany, which replicated the UK epidemiological research protocol [7]. The Bathing Water Directive (2006) is due to be re-examined in 2020.

The aim of this project was to conduct a rapid evidence assessment to evaluate the current epidemiological literature that examines the relationship between recreational water use (i.e. exposure to marine water and freshwater recreational waters) and gastrointestinal illness (GI), and to highlight any significant new research and/or evidence gaps which may help inform future bathing water quality guidelines. In the following section we provide a brief overview of the health risks associated with exposure to recreational bathing waters and of the European Bathing Directive.

1.1.1. Health and water quality

The majority of micro-organisms harmful to human health that are present in a water environment are faecal in origin. Faecal pathogens enter the water environment via multiple pathways, including treated sewage effluent discharges; sewer overflows; urban and rural diffuse pollution; and direct voiding of human, avian, wildlife and livestock faeces [8]. The degree of pollution from these sources varies depending on proximity to the source of pollution and the prevailing weather conditions [9].

[1] Bathing waters referred to here and covered by the Bathing Water Directive (2006) are untreated bodies of water, such as coastal and marine water, rivers, streams, lakes and estuaries. Swimming pools and waters for therapeutic purposes are not included.

Infection occurs when an individual consumes a sufficient quantity of contaminated water – either a small amount of highly contaminated water or a greater quantity of less contaminated water, although the amount necessary varies depending on the infective dose of any pathogens present. The risk of infection is therefore likely to be higher for individuals who (a) are exposed to more contaminated bodies of water; (b) spend a longer period of time in the water; (c) are likely to swallow more water, such as children and novice swimmers; and (d) have a compromised immune system, such as the very young or the very old. The health risks most closely associated with open water bathing are faecal-oral diseases which cause GI. Additional health risks include respiratory infections and ear, nose and throat complaints, although these health outcomes might not be directly associated with faecal organisms [10]. Examples such as the 2012 outbreaks of GI among swimmers who had participated in an organised swimming event in the Thames [11] and in Strathclyde Loch [12] highlight the important public health threat that poor water quality poses in the UK.

A causal relationship between exposure to polluted water and excess illness has been demonstrated in epidemiological studies [4 13 14]. These studies have informed the development of international standards for recreational bathing waters, including the WHO (2003) Guidelines for Safer Recreational Waters (updated in 2009), the US Environmental Protection Agency's Bacterial Water Quality Standards 2012, as well as the European Bathing Directive 2006 (2006/6/EC) [15]. This rapid evidence assessment focuses specifically on the quality standards in the European Bathing Directive (2006/6/EC).

1.1.2. The European Bathing Directive

The aim of the European Bathing Directive, revised in 2006 to update the original 1976 Directive, is to 'preserve, protect and improve the quality of the environment and to protect human health' [16]. As an EU member state, the UK is obligated to monitor the water quality of identified bathing areas throughout the bathing period. Monitoring activities are the responsibility of the devolved governments; in England Defra has overall responsibility for the Bathing Water Directive, and the Environment Agency oversees its administration through weekly water sampling of all coastal and inland designated bathing waters during the English bathing season (15 May to 30 September) [2]. Water samples are analysed in accordance with the reference methods, or their equivalents, specified in the Directive [1].

The revised Directive of 2006 will be fully in force by the end of 2014. Key features of the Directive include a new classification of bathing water quality based on more stringent standards of faecal indicator organisms (FIO) (namely, intestinal enterococci and *Escherichia coli* (*E. coli*)) and greater provision of public information to enable bathers to make a more informed decision on where and when to swim. The latter requires clearly displayed descriptions at identified bathing waters, covering a general description of the water body, details of any abnormalities and their expected duration, and information to bathers on where they can go to find out more information. In addition, from 2015 onward, the bathing water's classification, based on the previous four years of monitoring data (from 2012 to 2015), will also have to be displayed. Waters classified as 'poor' will be required to display a warning sign advising against bathing [17].

The revised Bathing Water Directive (2006) defines water quality standards based on confirmed intestinal enterococci and *E. coli*, as indicators of connectivity with faecal sources which may, at some point in the annual cycle, contribute faecal pathogens to the bathing water. Quality standards are based on the percentile value of faecal indicator organism concentrations over the past four bathing seasons. Starting in 2015, four bathing water classifications will be used: 'sufficient', 'good', or 'excellent'. Waters that do not satisfy the 'sufficient' standard will be considered as 'poor'. The limits for the classifications are shown in Table 1.

The classification standards are based on either a 90th or a 95th percentile value. It can be seen in Table 1 that the faecal indicator organism values for 'good' are set at a higher concentration than those for 'sufficient'. The 'sufficient' standard is based on a lower percentile value, 90 per cent, compared with 95 per cent for 'excellent' and 'good', allowing for greater variance in the sample quality. For example, for inland (fresh) waters and enterococci, for the 'sufficient' classification, there is a 1 in 10 chance that the sampled concentration of enterococci will exceed 330 CFU/100 ml, whereas for the 'good' or 'excellent' classification there is a 1 in 20 chance that concentrations will be greater than 400 CFU/100 ml and 200 CFU/100 ml, respectively [16].

Table 1. Faecal pathogen (Intestinal enterococci and *E.*coli) concentration upper limits for the bathing water classifications to be used from 2015, sourced from Annex I of the 2006 Bathing Water Directive [16]

Parameter	Quality			Reference method for analysis
	Excellent	Good	Sufficient	
Inland (fresh) waters				
Intestinal enterococci (CFU/100ml)	200[a]	400*	330[b]	ISO 7899-1 or ISO 7899-2
Escherichia coli (CFU/100ml)	500[a]	1000*	900[b]	ISO 9308-3 or ISO 9308-1
Coastal and transitional (marine) waters				
Intestinal enterococci (CFU/100ml)	100[a]	200[a]	185[b]	ISO 7899-1 or ISO 7899-2
Escherichia coli (CFU/100ml)	250[a]	500[a]	500[b]	ISO 9308-3 or ISO 9308-1

NOTE: [a] Based upon a 95-percetile, [b] Based upon a 90-percentile

1.1.3. Need for rapid evidence assessment

As noted above, the European Bathing Water Directive is due to be re-examined in 2020, and it is likely that the water quality standards will be reconsidered. This current rapid evidence assessment helps to identify the extent of the literature published since the 2003 WHO review and to determine whether there is any new evidence which indicates that a revision to the classification standards may be needed.

The concentration limits of faecal indicator organisms permitted for inland (fresh) waters are two times greater than those for coastal and transitional (marine) waters across all three classification standards. The US Environmental Protection Agency has not made the same distinction; it provides a single guideline value for enterococci that covers both marine and fresh water. Some commentators have suggested that the evidence to support the European decision to differentiate between water types is limited [18].

The current classification standards are based on epidemiological evidence collated by the WHO and are centred principally on UK studies using a randomised controlled trial protocol and healthy adult volunteers who were randomised into bathers and non-bathers. It is therefore not clear if the current standards are applicable to other groups of bathers. For example, it is not clear whether they are representative of the risk of illness for children [19] or other groups of recreational water users who may be more or less exposed to water than bathers, such as divers, surfers, boaters, and anglers.

Accordingly, the rapid evidence assessment aimed to answer the following research questions:

1. What is the post 2003 evidence for the health risks of recreational bathing in general – and also to specific groups of bathers?
2. What is the evidence to support the different classification standards outlined in the European Bathing Directive?

1.2. Objectives

The objectives of this rapid evidence assessment were to:

- Evaluate the current epidemiological literature post-dating the WHO Guidelines published in 2003 (including randomised controlled trials and other prospective studies) that examines the relationship between recreational swimming (i.e. bathing in the sea and in fresh water, such as lakes, ponds and rivers) and health, including studies of microbes in water and adverse health events reported by swimmers and appropriate controls;
- Identify if there are differences in bathing risk for different groups of people, including, but not limited to, the general public, children/babies, surfers, competitive swimmers, anglers, canoeists, boat users, and scuba divers;
- Present an overview of different indicator standards (i.e. current recommendations for quantitative levels of organisms in recreational water), including the FIO classification boundaries of the 2006/7/EC Bathing Waters Directive, and to evaluate if the current literature supports these indicators; and
- Identify any gaps in the literature.

1.3. Structure of the report

Following this introductory chapter, the following chapter describes the methods used to conduct this rapid evidence assessment, chapter 3 presents the core findings of the work (structured according to the type of water body), and chapter 4 presents a discussion of the results and presents research recommendations.

2. Methods

To address the above research questions/objectives, we undertook a rapid evidence assessment of the literature following the Joint Water Evidence Group (JWEG) guidance, as well as guidance published by the Centre for Reviews and Dissemination [20]. This methodology follows the process of a systematic review, but is considered a rapid evidence assessment because the search was limited to literature published from 2003 onwards.

2.1. Inclusion and exclusion criteria

In order to identify relevant studies, we defined 'PICOS' (Participants, Intervention(s), Comparison(s), Outcome(s) and Study types), some of which were common to both research questions, and others which were applicable to either one of the research questions. The PICOS are summarised in Table 2.and detailed below.

Table 2. Summary of inclusion/exclusion criteria

PICOS	Inclusion criteria	Exclusion criteria
Participants	Question 1[a]: Otherwise healthy humans who bathe in 'natural waters', including marine and fresh water; Specific groups of water-users including the general public, children/babies, elderly people, bathers, 'paddlers', surfers, competitive swimmers, anglers, canoeists, boat users, scuba divers.	Question 1: Studies that included bathers in recreational swimming pools, therapy pools, spas, etc,
	Question 2[b]: Studies that evaluate quantitative levels of different faecal organisms (other than viruses) in recreational natural waters as a measure of water quality. Eligible indicators include, but are not limited to, enterococci/faecal streptococci, and *Escherichia coli*.	Question 2: Studies that restrict analysis to cyanobacteria, viruses, or blue-green algae.

Interventions/ Comparators	Studies that compare - Polluted versus clean water; - Dose-related increases in faecal organisms; - Bathers versus non-bathers.	Studies that evaluate specific interventions such as UV treatment, and other chlorine-based disinfection systems for sewage (e.g. Elimbac).
Outcomes	Gastrointestinal infections (all case definitions used to define GI were eligible). The incidence rate) (or data that can be used to calculate incidence rates) and/or severity of the measure must be reported for example risk (RR or OR).	Outcomes relating to upper respiratory symptoms, ear and eye infections[c].
Study types	Randomised control studies (RCTs), quasi-randomised controlled trials, and prospective observational studies published from 2003 onwards.	Reviews, incident reports, letters, editorials.

NOTE: [a] Question 1: What is the post 2003 evidence for the health risks of recreational bathing in general – and also to specific groups of bathers? [b] Question 2: What is the evidence to support the different classification standards outlined in the European Bathing Directive? [c] These health outcomes were not assessed, as they might not be directly associated with faecal organisms. However, where these outcomes were reported, this has been documented in the data extraction table of included studies.

2.1.1. Participants

To address research question one (i.e. what is the post 2003 evidence for the health risks of recreational bathing in general – and also to specific groups of bathers?), eligible studies had to be conducted in otherwise healthy humans who bathed in 'natural waters', including coastal and transitional (e.g. marine and estuarine) and inland (fresh) water (e.g. lakes, ponds and rivers). We also included studies that evaluated specific groups of recreational water users including the general public, children/babies, elderly people, bathers, surfers, competitive swimmers, anglers, canoeists, boat users, scuba divers.

To address research question two (i.e. what is the evidence to support the different classification standards outlined in the European Bathing Directive?), studies had to evaluate quantitative levels of different faecal bacteria in recreational water as a measure of water quality. Eligible indicators include, but were not limited to, intestinal enterococci (e.g. confirmed faecal streptococci) and *E. coli*.

2.1.2. Interventions and comparisons

No interventions were evaluated in this rapid evidence assessment *per se*, however, we included studies that compared water bodies with varying microbiological quality, or studies that compared dose-related increases in organisms. We also included studies that compared outcomes for bathers versus non-bathers.

2.1.3. Outcomes

To address research questions one or two, eligible studies had to evaluate the incidences and/or risk of GI (e.g. Relative Risk (RR) or Odds Ratio (OR)) and/or severity. All case definitions used to define GI (as reported by the study authors) were included and reported.

2.1.4. Study designs

To address questions one or two, eligible studies included randomised control trials (RCTs), quasi-randomised controlled trials, and prospective observational studies. Case studies and incidence reports were also included in the search strategy (to scope the literature), but were not included in the analysis; these are listed in Appendix A. Reviews and systematic reviews were also excluded, but the reference lists were scanned for relevant studies. Studies published in conference abstracts were included as long as adequate data was reported.

2.2. Search Strategy

The literature search was conducted in a range of relevant databases such as PubMed and EMBASE and grey literature was searched via OAISTER, OpenGrey and NYAM Grey Lit. The list of databases searched is presented in Table 14, Appendix B. The search was limited to studies published from 2003 onwards up to December 2013. We searched for studies conducted in English, Spanish, Dutch, French, and German. Unpublished studies, including conference abstracts, were included if no other associated publication was found. The results of the searches were loaded into EndNote bibliographic software.

2.2.1. Search Terms

A pilot test of the search was conducted to ensure the terms were broad enough to capture a range of relevant studies and narrow enough that the search returned a manageable number of records. In our case, the pilot was successful and no further changes to the search terms were necessary. The search terms were mapped onto the subject indexing available in relevant databases and searched as text words in the titles and abstracts of records. The MEDLINE/PubMed search strategy was adapted to run in other databases. For example, for those without the ability to limit the search to human subjects, we added additional terms to “AND NOT”, such as frog, minnow, crustacean, etc. The complete list of search terms used in PubMed is presented in Textbox 1, Appendix B.

2.3. Study selection and data extraction

The ‘first pass’ was conducted by two individuals who independently screened titles and abstracts of all studies identified from the literature search in EndNote. Consensus was made on which papers were ordered for the ‘second pass’. In the ‘second pass’ full paper copies were screened against the inclusion/exclusion criteria by two independent reviewers, and any disagreements were resolved by consensus or by a third reviewer. Our expert advisors also screened the list of ‘second pass’ papers to ensure that no key publications were missing.

Study information (i.e. study characteristics, participant characteristics, study method, results, etc.) was extracted into Excel from the papers[2] by one reviewer and checked by a second reviewer. In addition, a sample of papers was checked by a third reviewer and any discrepancies were resolved through discussion.

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[2] These included full papers and one conference abstract.

If relevant outcome data were missing from the included papers, the study authors were contacted to obtain additional information.

2.4. Quality assessment

A quality assessment of each paper was conducted using published criteria. Randomised controlled trials were assessed using questions adapted from CRD (2009), and non-randomised trials (e.g. cohort and case-control studies) were assessed using the Newcastle-Ottawa scale [20 21]. Details for both criteria are provided in Table 15 and 16, in Appendix C. We also devised additional questions relevant to water quality studies (with guidance from our expert advisor Professor David Kay, Head of Centre for Research into Environment and Health of the University of Aberystwyth):

- Were the water quality samples collected near the exposed participants?
- Was a daily mean water quality assessment attributed to all participants exposed to water?
- Was a unique water quality sample attributed to each exposed person?
- How many water quality samples were taken (<20, >60, NR) to define each water quality exposure level used?
- How was 'treatment allocation' (exposure attribution) defined? (e.g. bather vs non-bather or specific water quality)
- Was there evidence that GI was not present at the start of the study?
- How was presence or absence of GI assessed? (e.g. self-reported, confirmed by doctor)
- Was follow-up long enough for outcomes to occur?
- Did the researchers investigate the effects of bias in the responders (for example, was each individual self-reporting or was one person replying on behalf of a family group)?

Quality assessments were conducted by one reviewer (recorded in Excel), and all were checked by a second reviewer, with any discrepancies resolved through discussion or by consulting a third reviewer.

2.5. Synthesising the evidence

We expected that this rapid evidence assessment would be largely quantitative. If the data had been suitable for pooling, meta-analysis would have been conducted. However, due to the considerable heterogeneity between studies in terms of settings, participants and protocols, it was not possible to conduct a pooled analysis. Instead, the evidence is summarised in tables and text by type of water (marine or fresh). In order to visually explore whether there are any patterns in the results, we have also presented the results graphically. It should be noted that these figures provide an alternative summary of the results to the tables and that no meta-analysis has been undertaken. More details are presented in section 0 onwards.

3. Evidence synthesis: Findings

Overall, 1,305 titles and abstracts were considered for screening. Based on the ‘first pass’ (title and abstract screened), 70 full text papers were screened for inclusion. Twenty papers and one conference abstract, representing 16 studies, met the inclusion criteria (see Figure 1). A list of the included papers, organised by study, is presented in Table 3. The complete list of the 70 papers reviewed, with reasons for exclusion (where applicable), is presented in Appendix D.

Figure 1. PRISMA diagram of literature search

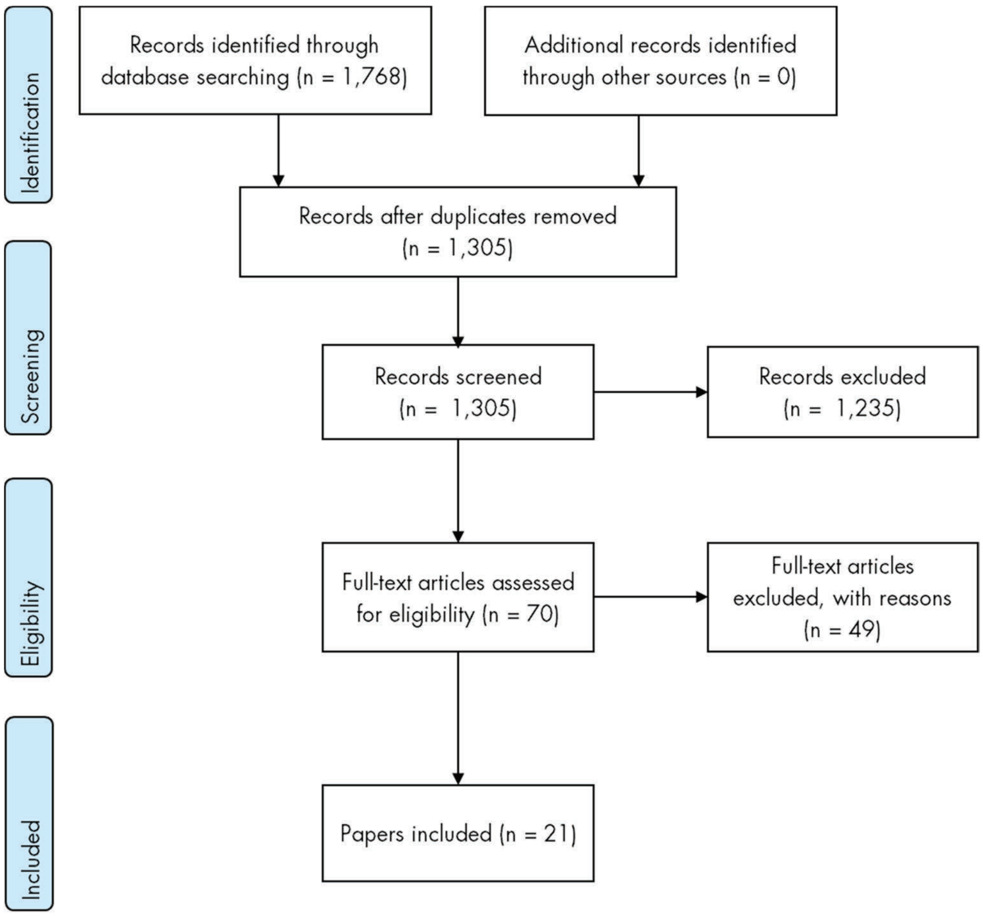

Table 3. Reference list for publications included in this review

No. Studies	Included papers	Study name (if given)
1	Abdelzaher AM, Wright ME, Ortega C, Hasan AR, Shibata T, Solo-Gabriele HM, et al. Daily measures of microbes and human health at a non-point source marine beach. Journal of water and health. 2011;9(3):443-57.	BEACHES
	Fleisher JM, Fleming LE, Solo-Gabriele HM, Kish JK, Sinigalliano CD, Plano L, et al. The BEACHES Study: health effects and exposures from non-point source microbial contaminants in subtropical recreational marine waters. International journal of epidemiology. 2010;39(5):1291-8.	
	Sinigalliano CD, Fleisher JM, Gidley ML, Solo-Gabriele HM, Shibata T, Plano LR, et al. Traditional and molecular analyses for fecal indicator bacteria in non-point source subtropical recreational marine waters. Water research. 2010;44(13):3763-72.	
2	Arnold BF, Schiff KC, Griffith JF, Gruber JS, Yau V, Wright CC, et al. Swimmer illness associated with marine water exposure and water quality indicators: impact of widely used assumptions. Epidemiology (Cambridge, Mass). 2013;24(6):845-53.	
3	Bonilla TD, Nowosielski K, Cuvelier M, Hartz A, Green M, Esiobu N, et al. Prevalence and distribution of fecal indicator organisms in South Florida beach sand and preliminary assessment of health effects associated with beach sand exposure. Marine pollution bulletin. 2007;54(9):1472-82.	
4	Colford JM, Jr., Schiff KC, Griffith JF, Yau V, Arnold BF, Wright CC, et al. Using rapid indicators for Enterococcus to assess the risk of illness after exposure to urban runoff contaminated marine water. Water research. 2012;46(7):2176-86.	
5	Colford JM, Jr., Wade TJ, Schiff KC, Wright CC, Griffith JF, Sandhu SK, et al. Water quality indicators and the risk of illness at beaches with nonpoint sources of fecal contamination. Epidemiology (Cambridge, Mass). 2007;18(1):27-35.	NEEAR[a] (but distinct from other NEEAR studies)
6	Cordero L, Norat J, Mattei H, Nazario C. Seasonal variations in the risk of gastrointestinal illness on a tropical recreational beach. Journal of water and health. 2012;10(4):579-93.	

No. Studies	Included papers	Study name (if given)
7	Dorevitch S, Dworkin MS, DeFlorio SA, Janda WM, Wuellner J, Hershow RC. Enteric pathogens in stool samples of Chicago-area water recreators with new-onset gastrointestinal symptoms. Water research. 2012;46(16):4961-72.	CHEERS
	Dorevitch S, Pratap P, Wroblewski M, Hryhorczuk DO, Li H, Liu LC, et al. Health risks of limited-contact water recreation. Environmental health perspectives. 2012;120(2):192-7.	
8	Dwight RH, Baker DB, Semenza JC, Olson BH. Health effects associated with recreational coastal water use: urban versus rural California. American journal of public health. 2004;94(4):565-7.	
9	Fleming LE, Solo GH, Elmir S, Shibata T, Squicciarini D, Jr., Quirino W, et al. A Pilot Study of Microbial Contamination of Subtropical Recreational Waters. Florida journal of environmental health. 2004;184:29.	
10	Harder-Lauridsen NM, Kuhn KG, Erichsen AC, Molbak K, Ethelberg S. Gastrointestinal Illness among Triathletes Swimming in Non-Polluted versus Polluted Seawater Affected by Heavy Rainfall, Denmark, 2010-2011. PLOS One. 2013;8:e78371-e78371.	
11	Marion JW, Lee J, Lemeshow S, Buckley TJ. Association of gastrointestinal illness and recreational water exposure at an inland U.S. beach. Water research. 2010 ;44(16):4796-804.	
12	Papastergiou P, Mouchtouri V, Pinaka O, Katsiaflaka A, Rachiotis G, Hadjichristodoulou C. Elevated bathing-associated disease risks despite certified water quality: a cohort study. International journal of environmental research and public health. 2012;9(5):1548-65.	GREEK
	Papastergiou P, Mouchtouri VA, Rachiotis G, Pinaka O, Katsiaflaka A, Hadjichristodoulou C. Bather density as a predominant factor for health effects related to recreational bathing: results from the Greek bathers cohort study. Marine pollution bulletin. 2011;62(3):590-5.	
13	Wade TJ, Calderon RL, Sams E, Beach M, Brenner KP, Williams AH, et al. Rapidly measured indicators of recreational water quality are predictive of swimming-associated gastrointestinal illness. Environmental health perspectives. 2006;114(1):24-8.	NEEAR[a] (but distinct from other NEEAR studies)
	Wade TJ, Calderon RL, Brenner KP, Sams E, Beach M, Haugland R, et al. High sensitivity of children to swimming-associated gastrointestinal illness: results using a rapid assay of recreational water quality. Epidemiology. 2008;19(3):375-83.	
14	Wade TJ, Sams E, Brenner KP, Haugland R, Chern E, Beach M, et al. Rapidly measured indicators of recreational water quality and swimming-associated illness at marine beaches: a prospective cohort study. Environmental health: a global access science source. 2010;9:66.	NEEAR[a] (but distinct from other NEEAR studies)

No. Studies	Included papers	Study name (if given)
15	Wade TJ, Converse RR, Sams EA, Williams AH, Hudgens E, Dufour AP. Gastrointestinal symptoms among swimmers following rain events at a beach impacted by urban runoff. American Journal of Epidemiology. 2013;177:S157.	
16	Wiedenmann A, Kruger P, Dietz K, Lopez-Pila JM, Szewzyk R, Botzenhart K. A randomized controlled trial assessing infectious disease risks from bathing in fresh recreational waters in relation to the concentration of Escherichia coli, intestinal enterococci, Clostridium perfringens, and somatic coliphages. Environmental health perspectives. 2006;114(2):228-36.	

NOTE: [a] A number of independent papers present results from the US National Epidemiological and Environmental Assessment of Recreational Water (NEEAR) study. The NEEAR studies have been commissioned as part of a collaborative research project between the US Environmental Protection Agency and the Centers for Disease Control and Prevention, which aims to determine how new ways of measuring water pollution can be effectively used to protect swimmers' health in both marine and fresh water. Thus, despite all these papers being classified as NEEAR studies, the results presented are independent.

3.1. Evidence synthesis

The key findings are presented in three sub-sections:

1. An overview of the included studies in terms of setting, participants, methodology used and the potential risk of biases (Section 3.2 (a table detailing the risk of bias for each study is presented in Appendix E); A description of the microbiological water quality as reported in the studies and a comparison of these against the quality standards as specified in the European Bathing Directive where possible (Section 3.3); and
2. Results for the risks of GI associated with water exposure (Section 3.4).

For each section, studies conducted in coastal and transitional (marine) waters and inland (fresh) waters are presented separately, referred to as marine or fresh water respectively from here onwards.

3.2. Description of included studies

Of the 16 included studies, 12 were conducted in marine waters (11 in coastal waters [22-35] and one in a coastal-lagoon [36]) and four were conducted in fresh waters [37-42]. Two of the included studies were pilot studies [31] [26] and one was a conference abstract [35]. The conference abstract was included in this rapid evidence assessment as it adds to the knowledge base regarding what studies have been conducted in this topic area.

Only two of the studies involved randomised controlled trials (considered to be the most robust type of quality design). The remaining 14 studies used an observational design: 12 used prospective cohorts, one was a retrospective cohort and one was a cross-sectional study. Table 4 provides an overview of the studies' characteristics ('n' indicates the number of studies). This table demonstrates that considerable variation exists between studies, particularly regarding water sampling method, definition of participant's exposure and definition of GI.

Table 4. Overview of study characteristics

General	
Time and place of study	Year (ranging from 2004 to 2013) Country (12 in US, 3 in Europe, 1 in Puerto Rico) Season (single [summer or winter] and multiple seasons evaluated) Precipitation rate (heavy rainfall vs little rainfall; various precipitation rates) Climate (Mediterranean type: n = 5, tropical: n = 1; subtropical: n = 3, temperate n = 7)
Age groups	Adults (n = 2) Children and adults (n = 11) Not reported (NR) (n = 3)
Water quality	
Type of water	Marine (n = 12) Fresh water (n = 4)
Source of pollution	Point (n = 3) Non-point (n = 6) Point and non-point (n = 2) Not reported (n = 5)
Collection of water samples	Individual samples taken by bathers (n = 1) Samples collected at a number of sites along the beach, at different times of day (n = 11) No direct water sampling (n = 2) Not reported (n = 2)
Methodology used for water analysis	Culture methods (n = 11) Plaque assay for viruses (n = at least 1) Fluorogenic and chromogenic substrate methods (n = 3) qPCR methods (n = 7) No water analysis conducted (n = 3) Not reported (n = 2)
Faecal organisms measured	*Enterococcus* (n = 11) *Escherichia coli* (n = 7) Faecal coliforms (n = 6) Total coliforms (n = 4) Somatic and male-specific coliphages (n = 2) Bacteroidales/Bactreriodetes (n = 2) *Bacteroides* (n = 2) *Clostridium* spp. or *Clostridium perfringens* (n = 3) *Staphylococcus aureus* (n = 2) *Vibrio vulnificus* (n = 1) *Cryptosporidium* spp. (n = 1) *Giardia* spp. (n = 1) Aeromonads (n = 1) Pyocyanine-positive *Pseudomonas* or *Aeruginosa* (n = 2)

Exposure – contact with water	
Reporting of exposure to water	Exposure to water determined by randomisation into exposure or non-exposure study groups (n = 2) Exposure self-reported by questionnaire (or reported by a family member for children) (n = 9) Exposure self-reported by interview (or reported by a family member) (n = 3) Other (n = 2)
Type of water contact of participants	Type of recreation: Swimming/bathing (n = 14) Surfing (n = 1) Limited-contact water recreation (canoeing, fishing, kayaking, motor boating or rowing) (n = 1) Extent of water contact (some studies reported more than one type of contact): Head immersion (n = 8) Body immersion (n = 5) Wading (n = 2) Any water contact (n = 6) Swallowing of water (n = 4) Exposure to wet sand (n = 1)
Outcome	
Reporting of GI	Self-reported by questionnaire (n = 3) Self-reported by telephone interview (n = 11) Self-reported by face-to-face interview (n = 11) Medical examination and face-to-face interview (n = 1) Time after exposure for reporting of illness ranged from 3 days to 3 weeks
Definition of gastrointestinal illness	Case definition used in the study (some studies used more than one definition): 1. Diarrhoea alone (n = 3) 2. All cases of vomiting or diarrhoea (three episodes of diarrhoea in 24 hrs) or all cases of indigestion or nausea accompanied by a fever (n = 2) 3. Nausea, diarrhoea, stomach pain or cramps (n = 2) 4. (a) Three episodes of diarrhoea in 24 hrs; (b) vomiting; (c) nausea with stomach ache; (d) nausea that interferes with regular activities; or (e) stomach ache that interferes with regular activities (n = 5) 5. (a) Three episodes of diarrhoea in 24 hrs; (b) vomiting; (c) nausea with stomach ache; (d) stomach ache that interferes with regular activities; or (e) stomach ache and fever (n = 1) 6. Diarrhoea and at least two of the following symptoms: vomiting, stomach cramps, fever, nausea, dizziness or headache (n = 1) 7. Any of the following symptoms: nausea, stomach ache, diarrhoea or vomiting (n = 3) 8. Two or more of the following symptoms: nausea/vomiting, abdominal pain, diarrhoea (defined as two or more loose or watery stools in a 24 hr period), fever (n = 1) 9. (a) Vomiting; (b) diarrhoea and fever; or (c) stomach pain and fever (n = 2) 10. (a) Vomiting; (b) diarrhoea and fever; (c) stomach ache or nausea accompanied with a fever (n = 1) 11. Diarrhoea or vomiting (n = 1) 12. Vomiting plus fever (n = 1) 13. Symptoms reported individually (n = 1)

Analysis	
Statistical analysis	Studies reported using one or more of the following statistical analyses: Chi-squared test (n = 3) Fisher's exact test (n = 2) Logistic regression (n = 14) Not reported (n = 1)
Examination of potential confounders (i.e. factors other than water quality that may potentially increase or decrease the risk of gastrointestinal illness)	Covariates monitored and included in the analysis varied by study. Examples of common covariates considered included: Eating or drinking at the beach Playing in sand Illness at baseline Contact with animals in past 48 hrs Consumption of meat and eggs Inter-household clustering Additional water contact during follow-up period

3.2.1. Marine water studies

A total of 12 studies, presented in 15 papers, were conducted in marine water [22-36]. Of these, ten investigated the risk of GI among bathers; six included bathers of all age groups, one included adults (over 18 years old) only, and three did not specify the age of the bathers. The remaining two studies were conducted among specific populations: surfers (aged 18 years or older) and triathletes (aged not specified).

Nine of the studies were conducted in the US: one in Alabama/Mississippi, four in California, three in Florida and one in South Carolina. Two studies were conducted in Europe: one in Denmark and one in Greece. One study was conducted in Puerto Rico.

Only one of the studies was a randomised control trial. The remaining 11 studies used an observational design: nine were prospective cohorts, one was a retrospective cohort, and one was a cross-sectional study.

For reference, each study is described separately below and summarised in Table 5. *Please note that the level of detail described below reflects what has been reported by the study authors.*

1. The Beach Environmental Assessment and Characterisation Human Exposure Study (BEACHES) was a randomised control trial conducted at a marine beach in Florida, US (sub-tropical climate), affected by non–point source pollution.[3] The study was reported in three included papers: Abdelzaher et al. 2011; Fleisher et al. 2010; and Sinigalliano et al. 2010. Water samples were collected following two protocols: (i) individual bather samples were collected by the participant from his or her designated 'bathing zone' at a water depth of knee height from just below the water's surface. The authors reported that a sample was taken from each bather to form a 'bather-collected' composite and that (ii) investigators collected two composite samples every 10 minutes, approximately 10 m away from the bathing zone. Water samples were analysed for intestinal enterococci using membrane filtration, chromogenic substrate and qPCR; faecal

[3] Non–point source refers to pollution from diffuse sources, such as land run-off, precipitation and drainage.

coliforms enumerated included *E. coli*, *Clostridium perfringens, Staphylococcus aureus*, *Vibrio vulnificus*, *Cryptosporidium* spp. and *Giardia* spp. Participants were assigned to an exposure status (bather vs non-bather) using block randomisation. The study investigators closely monitored participants' exposure (15 minutes in water at knee depth, complete head immersion three times) to ensure uniformity across participants. GI was self-reported by hard copy questionnaire completed 7 days after exposure. Participants with GI on the exposure day were excluded from the analysis. In total, 1,239 bathers and non-bathers were included in the final analysis. Logistic regression models controlled for age; gender; history of significant illness; use of medication within 4 weeks of exposure day; illness within 4 weeks of exposure day; illness in household after exposure; additional bathing after exposure; various measures of risk perception; and consumption of alcohol, mayonnaise, chicken, eggs, ice cream, salad, hamburgers, hot dogs, raw milk, meat pies, seafood, and purchased sandwiches in the 3 days before and 7 days after exposure. The method for collecting water samples appears to be rigorous, and it was feasible for authors to assign individual exposure data to participants. In order to minimise sampling error, bathers received training in how to take water samples [22-24].

2. The prospective cohort study by Arnold et al. (2013) was conducted at a non–point source coastal marine beach in Malibu, California (Mediterranean climate type). The authors reported that water quality samples were collected at five sites along the beach at 8:00 a.m. and 13:00 p.m. on each day of recruitment, and that the samples were collected at 0.5 m depth on an incoming wave. The researchers recorded the closest water sampling site to each adult participant and then attributed water quality averages of two samples (i.e. 08:00 a.m. and 13:00 p.m.) for each site to the bather. Several methods were used to evaluate enterococci, including EPA 1600, Enterolert, and three qPCR methods: Taqman Scorpion-1 and Scorpion-2; methods to evaluate *E. coli* and faecal and total coliform were also reported. In this study, the degree of exposure (i.e. body immersion to the waist, head immersion, and swallowing of water) and GI, were self-reported through a questionnaire, administered by telephone interview 10 to 19 days after exposure (median follow-up 11 days). Participants with GI at baseline were excluded from analyses in order to avoid confounding. The authors also conducted analyses to adjust for age, sex, ethnic background, length of follow-up >12 days, swimming on multiple days, allergies, contact with animals, contact with other sick people, frequency of beach visits, digging in the sand, and consumption of raw or undercooked eggs or meat. The methods used to collect water quality samples appear to have been adequate, but the average water quality of the two measures attributed to each bather as the exposure measure is likely to mask within-day variability in the FIO concentrations, leading to potential misclassification bias. A potential advantage in this regard is that the analysis was conducted on a large sample of participants (n = 5,674). There is also potential for self-selection bias (i.e. exposed bathers may have been more healthy at the outset than non-bathers). The authors also noted that there may be some risk of recall bias, as some follow-up interviews took place almost 3 weeks after exposure [25].

3. Bonilla et al. (2007) conducted a prospective cohort study on three south Florida beaches, US (sub-tropical climate) [26]. This was a pilot study with the principal aim of examining the prevalence of FIO in beach sand compared with water. A composite water sample was collected at low tide 5 m from shore at knee height from three locations (each site was sampled three times).

Samples were enumerated for enterococci using a culture method. Water samples were also analysed for faecal coliforms and somatic and male-specific coliphages. Exposure (measured as the number of hours spent in water) and GI were self-reported, at the same time, in a hard copy questionnaire completed 4 days after the beach visit. In total, 1,491 people were included in the epidemiological component of the study. Multiple logistic regression was used to investigate the impact of time of exposure and GI. As the authors did not report the location of water sampling in relation to bathers, it is not clear how representative water quality samples are of bather exposure. Exposure status was self-selected, and the authors note that bias is likely given the higher rates of GI observed among the control group (non-beachgoers from the general population). In addition, outcomes and exposure were self-reported, leading to the possibility of recall bias [26].

4. The prospective cohort study conducted by Colford et al. (2007) in the Mission Bay area, non–point source marine beaches in California, US (Mediterranean type climate), was part of the National Epidemiological and Environmental Assessment of Recreational Water (NEEAR) study [28]. Water samples were collected with varying frequency depending on the indicator organism and method. For *Enterococcus* samples enumerated following the EPA 1600 method, a composite water sample from all six study beaches was collected. Enterococci were also measured using a 96-well Quantitray based on hourly samples from each beach and qPCR based on two samples per day at each beach. The authors also reported results for total and faecal coliforms, *Bacteroides*, somatic phage and male-specific phage, adenovirus and norovirus. Elements of exposure status – principally, any water exposure and swallowing any water – was self-reported in a postal questionnaire. Information on GI was self-reported in a follow-up telephone interview 14 days after the beach visit. A total of 8,797 participants were included in the final analysis. Regression models were used to evaluate the association between risk of illness in swimmers and water quality based on a site-specific daily average of water quality. The reported model controlled for age, gender, ethnicity, chronic or existing illness and sand exposure. The number and location of water samples collected was not sufficient to measure an individual's exposure status, leading to potential misclassification bias. There was also the possibility of self-selection bias as a result of participants choosing their own level of exposure, and it can be seen that non-swimmers were likely to be older [28].

5. A separate prospective cohort study was conducted by Colford et al. (2012) at Doheny State beach in California, US (Mediterranean type climate) [27]. The beach is characterised by a naturally forming sand berm, which forms when the flow from the creek draining into the ocean is low, effectively damming the creek. When there is no berm (berm open days) the untreated water from the creek flows directly into the surf zone. Surface water samples were collected at a depth of 0.5 m on an incoming wave from five different locations (three points within 400 m of the creek mouth, one in the creek and one 3000 m south of the creek) at three time points during the day: 08:00 a.m., 12:00 p.m. and 15:00 p.m. Enterococci were enumerated following the EPA 1600 method, as well as Enterolert and three qPCR methods (Taqman, Scorpion-1, and Scorpion-2). In addition, samples were analysed for total and faecal coliforms. Exposure descriptors (i.e. body immersion, head immersion and swallowing of water) were self-reported to investigators on the day of the beach visit. GI outcomes were self-reported by participants in a

telephone interview conducted 10 to 14 days after the beach visit. In total, 9,525 people were included in the analysis. Regression models controlled for study year, age, gender, ethnicity, swimming on multiple days, allergies, contact with animals, contact with other sick people, frequency of beach visits, digging in sand and consumption of raw or undercooked eggs and meat. The investigators assigned a site-specific daily average of all morning and afternoon sample values to the site nearest to the participant's exposure, thus reducing the likelihood of misclassification bias. Exposure status was not randomly assigned, leading to the potential for self-selection bias; bathers were more likely to be male and non-bathers were more likely to be female [27].

6. Cordero et al. (2012) conducted a prospective cohort study at a marine beach in Puerto Rico (tropical climate), which was reported to have both point and non–point sources of pollution [29]. Water quality samples were collected from along three transects placed 60 m apart perpendicular to the shoreline, at shin and waist height water depth, in areas with the highest swimmer density. Samples were taken at three points of time during each day of the study: 10:00 a.m., 12:00 p.m. and 14:00 p.m. An additional composite sample (combined water sample from shin and waist height) was taken from each transect at each time point. Water samples were enumerated for enterococci following the EPA 1600 method and using qPCR. In addition, the study authors tested water samples for faecal coliforms and Bacteroidales. Exposure status (water contact vs no water contact) was self-reported on the day of the beach visit in an interview. A follow-up interview was conducted 10 to 12 days after the beach visit to ascertain GI. The final cohort had 1,457 participants (315 during autumn and 1,142 during summer). The authors investigated (i) differences in the incidence of GI between bathers and non-bathers and (ii) the risk of illness predicted by water quality among bathers using logistic regression, based on daily average value of water quality samples. Models controlled for age, gender, sex, chronic GI and sand exposure and adjusted for inter-household correlation. A daily average was assigned to participants, which could mask potential fluctuations in the water quality throughout the day. However, the study authors reported no significant difference in water quality between collection times. Exposure was not randomly assigned, leading to the potential for self-selection bias; non-swimmers were older on average than swimmers [29].

7. Dwight et al. (2004) conducted two cross-sectional surveys in 1998 and 1999 among surfers at two non–point source–impacted beaches in California, US (Mediterranean type climate) [30]. The authors did not conduct any water sampling; water quality was estimated based on total coliform data published by the Orange County and Santa Cruz health agency. Participants reported GI and the amount of time they were exposed to coastal water in the past 3 months in an interview with study investigators. In total, the analysis included 853 participants in 1998 and 1,020 in 1999. Occurrence of GI was classified as a binary variable (have or have not had GI in past 1 month), and logistic regression was used to compare rates of illness between years. The likelihood of misclassification bias is high because mean monthly water quality measurements and self-reported length of water contact was used to approximate an individual's exposure. This also meant that the authors were unable to determine which indicators were associated with illness. Participants were asked to recall episodes of GI and the number of times they had been surfing in the past 3 months, introducing the potential for recall bias [30].

8. The prospective cohort study conducted by Fleming et al. (2004), which evaluated 208 bathers (of all ages) at two marine recreational beaches in Florida, US (sub-tropical climate), was a pilot study [31]. Water samples were collected daily for the duration of the study, but further details were not reported. Water samples were enumerated for enterococci, *E. coli*, faecal and total coliforms and *C. perfringens*. The method of analysis was not reported. Exposure (face immersed in water) was self-reported by participants to the study investigators on the day of the study. GI was self-reported 8 to 10 days after exposure. The study was not well reported and it is therefore difficult to make an assessment of risk of bias [31].

9. The retrospective cohort study by Harder-Lauridsen et al. (2013) was conducted in a coastal lagoon near Copenhagen, Denmark (temperate climate) and aimed to compare illness among triathletes competing in two different years with differing water quality [36]. Water quality was modelled for enterococci and *E. coli* based on a real-time forecasting system developed by the Danish Hydraulic Institute Group. GI was self-reported via an electronic questionnaire; the length of follow-up was 1 month after the event in 2010 and 2 weeks in 2011. Estimates of the amount of water swallowed were also recorded. In total, there were 838 participants in 2010 and 931 participants in 2011. Logistic regression was used to estimate the relationship between illness and water quality. It is not clear what other variables the model controlled for [36].

10. The Greek Bathers Cohort study was conducted at three marine beaches subject to non–point source pollution in Greece (Mediterranean climate) [32 33]. Water quality samples were collected once per day (between 10:30 a.m. and 12:30 p.m.) from each of the seven sampling points located along the beach line at the point with the highest bather density. Samples were analysed for enterococci, *E. coli*, total and faecal coliforms and *Staphylococcus aureus* using a culture method. Exposure (body immersion for at least 10 minutes) status was self-reported in a face-to-face interview on the day of the beach visit, and any development of GI was self-reported in a telephone interview conducted 10 days after exposure. In total, 4,377 people were included in the final logistic regression model. Models were controlled for age, gender and place of residence. The water quality samples were taken at only one point of time during the day; the participants were thus not assigned individual exposure status, leading to the potential for misclassification bias. Participants self-selected their exposure status; the authors reported that the control group (i.e. people who had not visited a beach) was more likely to be old or ill as a result of selection bias. The definition of exposure could have resulted in an underestimation of risk, as it did not account for time spent in the water and includes those who did and did not immerse their head and those who did or did not swallow any water [32 33].

11. The prospective cohort conducted by Wade et al. (2010) was part of the NEEAR study [34]. The study took place at three marine beaches affected by treated sewage in Mississippi and Alabama, US (temperate climate). The method for water sampling followed Wade et al. (2006 & 2008); samples were collected three times a day (at 8:00 a.m., 11:00 a.m. and 15:00 p.m.) along three transects placed 60 m apart perpendicular to the shoreline. Two samples were collected along each transect, one at waist height and one at shin height water depth. Water samples were analysed for enterococci using culture methods and qPCR; the author also reported methods for total Bacteroidales species and *Clostridium perfringens*. The authors recorded self-reported

exposure (body immersion and head immersion) in a questionnaire on the day of study. GI was also self-reported in a telephone interview 10 to 12 days after beach visit. A total of 6,350 participants were included in the study. Those reporting GI within 3 days before their beach visit were excluded from the analysis. Logistic regression models were controlled for age, gender, race, contact with animals, other swimming in the past 1 week, contact with other persons with diarrhoea, distance travelled to beach, chronic illness, digging in sand, use of insect repellent, consumption of raw/undercooked meat, and environmental factors. The water quality sampling was undertaken near participants and at different time points during the day. However, individual exposure was not assigned to participants; results were presented for morning samples (8:00 a.m. and 11:00 a.m.) and pooled to estimate a daily mean average, leading to the potential for misclassification bias. There is the potential for further misclassification bias because results were combined for all exposure statuses (body immersion or head immersion) [34].

12. The prospective cohort study by Wade et al. (2013) was conducted on a marine beach impacted by urban run-off in South Carolina, US (temperate climate), and is presented in a conference abstract [35]. The methodology used for measuring water quality was not presented in the abstract. GI was self-reported in a telephone interview 10 to 12 days after beach visit. In total 11,519 participants were enrolled, but it is not clear how many were included in the final analysis. A description of the statistical analysis was also not reported. It is not possible to accurately assess the study for bias as insufficient information is provided [35]. When we contacted the study author for further information, we were informed that the results will be published shortly.

Table 5. Descriptive overview of marine water studies

Author/year/study name	Type of water/brief description	Study location/country and climate/season	Study design	Study objective (as stated by study authors)	Sample size/details /comparator conditions (if applicable)	Summary of participants/definition of water exposure	Inclusion and exclusion criteria (as reported by study authors)	List of all outcomes evaluated in the study	How was the outcome 'GI' defined/assessed by the study authors?	Methodology (water quality sampling)	Faecal organisms evaluated/method or technique used to measure faecal organisms (e.g. culture, qPCR)
Abdelzaher AM, Wright ME, Ortega C. et al. 2011; Sinigalliano CD, Fleisher JM, Gidley ML et al. 2010; Fleisher JM, Fleming LE, Solo-Gabriele HM et al. 2010 the BEACHES study	Non-point-source-polluted marine recreational beach. 1.6 km long, relatively shallow, characterised by weak water circulation The beach violates regulatory monitoring criterion 2.1 times per year, averaged from 2002 to 2010	Miami, Florida, US Subtropical; average ambient temperature 24.8°C December 2007 to June 2008	RCT	This study evaluated water quality and daily cumulative health effects, including gastrointestinal, skin and respiratory illnesses, for bathers at a non-point-source-polluted subtropical marine recreational beach in order to better understand the inter-relationships between these factors.	In total, 1,303 people enrolled. Analysis excluded participants with pre-existing illness, resulting in N = 1,239.		Adults (≥18 yrs) who report regularly bathing in southern Florida	-Water quality -Health outcomes (gastrointestinal, skin, eye or ear infections; respiratory illnesses)	Self-reported by participants using a questionnaire 7 days after exposure; GI was defined as the report of (1) all cases of vomiting or diarrhoea or (2) all reported cases of indigestion or nausea accompanied by a fever; diarrhoea was defined as having three or more runny stools in a 24 hrs	Two types of water samples were collected: 'individual' samples by individual bathers and 'daily composite samples'. 15 sampling events were conducted on 15 different days Individual bather samples: bathers each collected 5 l water samples from their area of exposure (a 30–40 m stretch of beach was subdivided at 5 m intervals to form bathing zones) at knee depth (which varied with the tide) just below the water surface. Bathers received training in order to minimise variation among individuals. 1L from each sample was collected in a 'bather-collected composite' sample. Investigator composite sample: two 20 l samples collected at knee depth every 10 mins throughout the 3.5 hrs of sampling, collected approx 10 m away from bathing zone. N = NR	Enterococci; pathogens evaluated included bacteria (*Staphylococcus aureus* by MF, *Vibrio vulnificus* with enrichment by MF and confirmation by PCR) and protozoa, which were processed using a low-concentration method (*Cryptosporidium* spp. and *Giardia* spp. via qPCR).
					Adult bathers: n = 652	Participants reported regular bathing in southern Florida Bathers were asked to spend 15 min in water at knee depth and to immerse their head three times Mean age: 32.2 (SE 12.64) Sex: female 49.27%					
					Non-bathers: n = 651	Non-bathers were asked to spend 15 min sitting on chairs on plastic sheeting on a cordoned-off section of the beach Mean age 32.5 (SE 13.4) Sex: female 50.73%					

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Arnold BF, Schiff KC, Griffith JF et al. 2013	Non-point-source-polluted coastal marine beach The beach is located at the mouth of the 282 km^2 Malibu Creek watershed. About 38 million l (10 million gallons) per day of treated effluent are discharged into the watershed from November to March. There was no discharge during the study period.	Malibu Beach, California, US May to September 2009	Prospective cohort	To report illness risk from swimming at a marine beach affected by non-point sources of urban run-off, measure associations between faecal indicator bacteria levels and subsequent illness among swimmers, and investigate the sensitivity of results to a range of exposure and outcome definitions.	5,674 people in total		1) At least one household member at the beach was aged ≥ 18 yrs 2) Home address was in the US, Canada, or Mexico 3) No previous study participation in the past 28 days 4) Ability to speak English or Spanish 5) Anyone with illness at enrolment was excluded	-Water quality -Health outcomes (diarrhoea, gastrointestinal illness, skin rash, eye infection, earache, fever, urinary tract infection and upper respiratory illness)	Illness in the 3 and 10 days following exposure self-reported by participants using a questionnaire, with a follow-up interview 10–19 days after exposure; diarrhoea was defined as having three or more watery stools in 24 hrs; GI was defined as (1) diarrhoea, vomiting, nausea and stomach cramps; (2) nausea and missed daily activities due to GI; or (3) stomach cramps and missed daily activities due to GI.	Water quality samples were collected at five sites along the beach. On each recruitment day, water quality samples were collected at 8:00 a.m. and 13:00 p.m. at 0.5 m depth on an incoming wave. Interviewers recorded the closest water sampling site to each participant. N = 307	Enterococci; *E. coli* All samples for culture and defined-substrate technology methods were processed immediately; filters for three qPCR methods were frozen for later analysis. Sand samples (200 g) were shaken vigorously in 500 ml of water. Samples processed using membrane filtration, as described by US EPA, to measure for total faecal coliformd and *E. coli*. To test for coliphages, samples were enumerated by plaque assay.
					Swimmers; body immersion (BI) n = 2,559 (analysis excluded 83 because didn't have location, n = 2476) head immersion n = 1,849; swallowed water n = 571) (data not reported together)	Swimmers: body immersion to the waist, head immersion and swallowed water HI = head immersion BI = body immersion SW = swallowed water Bathers of all age groups Age: 0–5 years: 12% (BI); 9% (HI); 17% (SW) 5.1–10: 17% (BI); 17% (HI); 22% (SW) 10.1–20: 19% (BI); 21% (HI); 17% (SW) 20.1–30: 17% (BI); 17%) HI); 16% (SW) 30.1–40: 15% (BI); 16% (HI); 14% (SW) 40.1–50: 12% (BI); 12% (HI); 8% (SW) >50: 8% (BI); 8% (HI); 5% (SW) Sex: female 44% (BI); 38% (HI); 41% (SW)					
					Non-swimmers (n = 1,895)	Age: 0–5 years: 8% 5.1–10: 2% 10.1–20: 9% 20.1–30: 22% 30.1–40: 23% 40.1–50: 20% >50: 16% Sex: female 64%					
Bonilla TD, Nowosielski K et al. 2007	Nearshore waters of southern Florida, US, marine beach	Three southern Florida, US, beaches; Hobie Beach (on sheltered Biscayne Bay), Hollywood Beach, and Ft. Lauderdale Beach (both on Atlantic Ocean) July 2001–July 2002 Fr. Lauderdale Beach; July 2001–July 2003 Hobie Beach, Hollywood Beach	Prospective cohort	This was a pilot study to examine the prevalence of faecal indicator organisms in tidally affected beach sand and in upper beach sand compared with counts in water.	1491 people in total			-Water quality -Health outcomes (gastroenteritis, dermatological, upper respiratory, constitutional)	Self-reported. Participants were provided with a questionnaire if they agreed to participate and asked to complete it 4 days after beach visit;, no other details provided. Fourteen symptoms listed grouped into four categories; symptoms listed for GI: nausea, diarrhoea, stomach pain or cramps	Study sampled sand and water. Samples obtained from three sites along a transect line during low tide: (1) water site taken 5 m from shore at knee height, (2) wet sand taken mid-way between the current water level and the high tide level, (3) dry sand site taken 5 m above the high tide line. Total 576 sand samples and 288 water samples.	Faecal coliforms, enterococci, *E. coli* (membrane filtration), somatic and male-specific coliphages (culture); sand samples (200 g) were shaken vigorously in 500 ml of water. Samples processed using membrane filtration, as described by US EPA, to measure for total faecal coliforms and *E. coli*. To test for coliphages, samples were enumerated by plaque assay.
					Beachgoers n = 882	(1) people exposed to dry sand only (2) people exposed to wet sand only (3) people entering water without significant exposure to either wet or dry sand					
					Non-beachgoers n = 609	randomly selected from general population	Should not have visited a beach in at least 9 days.				

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Colford JM, Wade TJ, Schiff KC et al. 2007 Part of the National Epidemiological and Environmental Assessment of Recreational Water (NEEAR) study	Non-point-source-polluted marine recreational beaches	Six Mission Bay beaches, California, US Memorial Day (end of May) to Labor Day (beginning of September) 2003	Prospective cohort	To examine health effects experienced by swimmers and the relationship of these effects to water quality indicators in water in which non-human faecal sources dominate.	n = 8,797 in total		1) No previous participation in the study 2) At least one household member at the beach was aged ≥ 18 years 3) Home address was in the US, Canada, or Mexico 4) No history of swimming in the previous 7 days	-Water quality -Health outcomes (gastrointestinal, skin and respiratory illnesses)	Self-reported via telephone interview 14 days after beach visit GI symptoms included nausea, vomiting diarrhoea, and stomach cramps. In addition, two levels of credible GI were measured: HCGI-1, either (1) vomiting; (2) diarrhoea and fever; or (3) cramps and fever, and HGCI-2, vomiting plus fever	Samples were collected on 29 days, at the 6 beaches at 18 sites. The number of sampling sites ranged from 2–5 per beach, depending on beach length and anticipated swimming activity. Samples were collected with varying frequency depending on the specific indicator. N = 1,892	*Enterococcus* (EPA 1600 (beach composite once per day), 96-well Quantitray (hourly sample at every site), qPCR (two samples per day at each site)), total coliforms, faecal coliforms (APHA Method 9222D, 96-well Quantitray). Traditional membrane filtration methods, chromogenic substrate method, qPCR
					Bathers of all age groups Swimmers: (n = 4,971, 57%)	Any water contact at the beach and swallowing any water Age: 0–5 years: 18% 5.1–12: 29% 12.1–30: 24% 30.1–55: 25% >55: 2% Sex: female 46%					
					Non-swimmers: (n = 3,742, 43%)	No Contact with water Age: 0–5 yrs: 9% 5.1–12: 9% 12.1–30: 30% 30.1–55: 44% >55: 7% Sex: female 43%					
Colford JM, Schiff KC, Griffith JF, 2012	Marine recreational beach. This beach had two conditions: sand berm open (i.e. the untreated creek flow discharged directly to surf zone and increased Faecal Indicator Bacteria concentration) and sand berm closed (with generally improved water quality). The berm naturally forms when the flow from the beach is low, effectively damming the creek. This beach is chronically listed as one of the most polluted beaches in California.	Doheny State Beach in Dana Point, California, US Subtropical (described as a Mediterranean climate) Summers of 2007 and 2008	Prospective cohort	To assess the relationship of rapid indicator methods (qPCR) to illness at a marine beach impacted by urban run-off.	n = 9525	Mean age: 29 years Sex: female 53%	1) No previous participation in the study 2) At least one household member at the beach was aged ≥ 18 years 3) Home address was in the US, Canada, or Mexico 4) Verbal Consent	-Water quality -Health outcomes (gastrointestinal, including nausea, vomiting, diarrhoea, stomach ache, abdominal cramps, skin and respiratory illnesses) Swimmers (BI, HI and SW) vs non-swimmers.	Self-reported via telephone interview 10–14 days after beach visit. GI outcomes included nausea, vomiting, diarrhoea (three or more runny stools within 24 hrs), stomach ache and abdominal cramping. HCGI was defined as: (1) diarrhoea; or (2) vomiting; or (3) nausea and stomach cramps; or (4) nausea and missed daily activities due to GI; or (5) stomach cramps and missed daily activities due to GI	Surface water samples collected at 0.5 m depth on an incoming wave at three times during the day (8:00 a.m., 12:00 p.m. and 3:00 p.m.) at five beach sites. Sites A, B and D were within 400 m of the creek mouth; site C was in the creek; and site E (reference site) was 3000 m to the south. N = 481	*Enterococcus*, total coliforms, faecal coliforms Samples for culture methods were processed immediately, while filters for the three qPCR methods were frozen for later processing. Faecal and total coliforms were measured using traditional membrane filtration; enterococci was measured , using culture techniqyes (EPA 1600 and Enterolert), and using rapid indicators (qPCR) (Taqman, Scorpion-1 and Scorpion-2 qPCR).
					Bathers: (n = 5940) Body immersion (n = 4335, 46%) Head immersion (n = 3290, 35%) Swallowed water (n = 1219, 13%)	Bathers: Mean age: 26 yrs Sex: female 50%					
					Non-bathers: n = 3585, (38%)	Non-bathers Mean age: 37 years Sex: female 61.8%					

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Cordero L, Norat J, Mattei H, Nazario C, 2012	Potential point- and non-point-source-polluted marine recreational beach Sources of water discharge are listed as wastewater treatment works, storm water sewer, Sabana River, and a creek	Costa Azul Beach, Luquillo, Puerto Rico Tropical Two seasonal periods in 2008: (1) 14 June to August 3, (2) 14 September to 19 October Conducted mostly on Sundays, 10:30 a.m.–5:00 p.m.	Prospective cohort	To obtain more information about the possible health hazards associated with bathing in Puerto Rico's tropical marine environment and to compare different recreational water quality indicators.	Incidence of GI available from 1,299 individuals. Multivariate model includes 1,457 individuals (1,142 summer and 315 autumn)		Exclusion: (1) participation in the study in the past 28-day period; (2) unaccompanied minors (<18 years); (3) inability to speak Spanish or English (4) body immersion without head immersion	-Water quality -Health outcomes (GI, respiratory, ear, eye, skin rash symptoms)	Self-reported using a telephone interview. Participants were interviewed at the beach using a standard questionnaire from EPA (which had previously been used for the National Epidemiological and Environmental Assessment of Recreational Water Study). Follow-up interviews were conducted 10–12 days after beach visit to collect information about health symptoms. GI defined as any of the following: (1) diarrhoea – i.e. having >3 loose stools within a 24 hr period; (2) episodes of vomiting; (3) nausea and stomach ache; (4) stomach ache that affected regular activity; or (5) stomach ache and fever	The beach was divided into three transects >60 m apart in order to encompass the swimming area. Samples were taken along the transect at shin and waist height; a third, composite sample (shin and waist height water) also taken. Sampling was repeated at 10:00 a.m., 12:00 p.m. and 14:00 p.m. Summer N = 144, autumn N = 90	Enterococci, faecal coliforms, *Bacteroidales* samples analysed within 6 hrs using membrane filtration or culture methods, as well as qPCR analysis. *Enterococcus* was enumerated using US EPA Method 1600 on membrane-*Enterococcus* idoxyl-β-D-glucoside agar (mEI) plates. Faecal coliforms were enumerated using the American Public Health Association method 9222D on membrane-faecal coliform agar plates.
					Bathers: n = 921 (71%) (summer 750, autumn 171)	Beachgoers Bathers: completely immersed head and body Mean age: 26 yrs (SD 16.4) Sex: female 50% Potential confounding factors: 86.2% ate/drank at beach; 30.78% experienced sand exposure (collecting shells, making sand castles, burying body in sand, getting sand in mouth, digging in sand); 3.88% suffered from chronic GI.					
					Non-bathers: n = 378 (29%) (summer 207, autumn 108)	Non-bathers (spent the day at the beach but did not have any water contact, i.e. did not wade, play in the water or swim) Mean age: 37 yrs (SD 17.9)					
Dwight, RH Baker, DB Semenza, JC Olson, BH. 2004	Non-point-source-polluted recreational marine beaches (one urban with highly polluted run-off and one rural), each assessed in two different years with different precipitation rates	Urban North Orange County (NOC) and rural Santa Cruz County (SCC). California, US Winter months (January to April) (In 1998 El Niño had led to record-high precipitation throughout California. In 1999 El Niña had led to record-low precipitation in NOC. NOC had lower total rainfall than SCC in both years.)	Two cross sectional surveys	To gather data on reported health symptoms (e.g. vomiting, diarrhoea, sore throat) experienced by surfers in two areas to determine whether symptoms were associated with exposure to urban run-off.	Total urban: n = 1,141 (i.e. with highly polluted run-off water) Total rural: n = 732	Mean age: 30 yrs Sex: male 93% (data were not reported by group)	Surfers (individuals who had wetsuits and surfboards) who reported surfing at least once a week and were 18 years or older.	-Health symptoms (any symptom, significant respiratory disease, HCGI, fever, nausea, stomach pain, vomiting, diarrhoea, sinus problems, cough, phlegm, sore throat, eye redness, ear pain, skin infection)	Self-reported by participants in a face-to-face interview. Information on symptoms experienced during the previous 3 months and the time of exposure to coastal waters were reported. HCGI defined as (1) vomiting, diarrhoea and fever; or (2) stomach pain and fever.	No water sampling. The authors used data from OC heath care agency and SC health agency regarding mean monthly total coliform counts (per 100 ml). Not measuring water quality at the sites meant that they were unable to determine the specific nature of the pollutants associated with symptoms. N = NR	NR
					1,998 853 surfers (479 in urban NOC 374 in rural SCC)						
					1999 1020 surfers (662 in urban NOC 358 in rural SCC)						

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Fleming LE, Solo GH, Elmir S et al. 2004	Marine recreational beaches, two beaches analysed, located within 1.6 km of each other	Miami, Florida, US Subtropical April and July (year not reported)	Prospective cohort	A prospective cohort pilot study was performed to evaluate the relationship between microbial water quality indicators and public health in subtropical recreational marine waters.	n = 208 Beach 1 (n = 99) Beach 2 (n = 109)	Beach 1: Families: Bathers of all age groups Mean age: 19.9 yrs (SD 15.9) Sex: female 20% Beach 2: Mean age: 21.1 yrs (SD 17.4) Sex: female 27%	1) Miami Dade County Residents 2) People who immersed their face in the beach water on the day of enrolment 3) People who had not been at the beach in the past 7 days (tourists and non-residents were excluded)	-Water quality -Diarrhoea (blood in stool) -Vomiting -Stomach pain, skin rash, infected cuts, eye redness, earache and ear discharge, fever, chills, nasal congestion, cough (with phlegm) and sore throat	After initial interview at the beach at time of enrolment, outcome was defined by self-reported telephone interview 8–10 days after exposure. GI symptoms defined were diarrhoea and stomach pain. Inferred symptoms were nausea and vomiting.	Samples were collected every day for 1 month in the dry season (April) and 1 month in the wet season (July). Conducted in three phases: 1: daily water quality monitoring based on CFU/100 ml, 2: beach sand sampling, beach 1 only mentioned, 27 sampling points in submerged, sea weed–covered and uncovered sand, 3: spatially intense water sampling, 58 samples collected from beach 1. N = NR	Enterococci, faecal and total coliforms, *C. perfringens* and *E. coli* Method: NR
Harder-Lauridsen et al. 2013	Coastal lagoon just to the east of the city of Copenhagen. Assessed in two different years with different precipitation rates.	Amager Beach Park Lagoon, Denmark August 2010 and August 2011	Retrospective cohort	To determine the extent and identify the source of illness among athletes participating in a triathlon competition.	2010 838 participants (water was more polluted) 2011 931 participants (water was less polluted)	2010: Swimmers participating in a race Age: <38 yrs 47.1% Sex: female 13.4% 2011: Age: <38 yrs, 58.5% Sex: female 13.5%	Participants in the 2010 and 2011 Challenge Copenhagen Ironman Triathlon competition (3.8 km swim)	-Health outcome (GI; individual symptoms of diarrhoea, vomiting, stomach cramps, fever, nausea, bloody diarrhoea, headache, tenesmus, muscle pain; severity of disease assessed by visit to physician, absence from work, exhaustion) –Stool samples	Self-reported in an electronic questionnaire, sent 1 month after 2010 event and 2 weeks after 2011 event. Two definitions: (1) participants reporting having suffered diarrhoea or vomiting in the days following the competition, and (2) participants who indicated having had diarrhoea and at least two of the following symptoms: vomiting, stomach cramps, fever, nausea, dizziness or headache	Data were used from a real-time bathing water quality forecast system developed by DHI Group in Denmark, which models concentrations of two indicator bacteria (*E. coli* and enterococci) N = NR	Enterococci; *E. coli* Method: NR

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Papastergiou P, Mouchtouri V, Pinaka O, Katsiaflaka A, Rachiotis G & Hadjichristodoulou, 2012; same authors, 2011 Greek bathers cohort study	Marine beach Beach A is a wide sandy beach in front of a small village which does not have main sewerage. Parallel to the beach and about 100 m behind the shore was an influent of a nearby river that flows in the beach. Beach A is considered higher risk for water contamination. Beaches B and C had similar geophysical characteristics, both were pebbled beach.	Three different bathing sites in Melivia and Evrymenes, Greece. Weekends (Friday, Saturday, Sunday) during the summer bathing period 2008	Cohort study	To assess the risks of symptoms related to infectious diseases among bathers after exposure to sea water which was of excellent quality according to EU guidelines and the US EPA.	n = 4377 in total. Majority were resident in the wider area of Thessaly	-	Emigrants, foreign tourist and Roma community excluded (based on socioeconomic, cultural and behavioural differences that might have an impact)	-Water quality -Health outcomes (nausea or vomiting, abdominal pain, diarrhoea more than two times, fever, GI, sore throat, dysphagia, rheum, cough, hoarseness, respiratory (2 definitions), ear, eye and cutaneous infections, UTI, vaginitis, medical consultations, medication received and hospitalisation/home care.)	Face-to-face interviews were conducted to collect information on demographics, bathing behaviour, aesthetic appeal of the beach, and day of bathing. All members of a household participated. A follow-up interview was conducted 10 days later by telephone to gather information on symptoms of potential bathing-related diseases. GI: nausea/vomiting, abdominal pain, diarrhoea (defined as two or more loose or watery stools in a 24 hr period), fever. Two definitions were used; A (sensitive) required a positive answer to one of the symptoms listed and B (specific) required two or more symptoms. Fever could be included in definition B but not A.	Samples taken and analysed on the same day that the questionnaire took place (67 from beach A, 61 from beach B, 21 from beach C). Beaches A and B had 3 sampling points and beach C had 1.. All sampling points were located along the beach line. One sample was collected from each sampling point in the morning between 10:30 a.m. and 12:30 a.m. Information was also gathered on bather density, water temperature, presence of high waves, wind direction, phenolic smell, garbage, wrack and oil or tar on the beach or sea. N = 149 (Beach A 67, Beach B 61, Beach C 21)	Enterococci, *E. coli*, faecal coliforms, total coliforms, *Staphylococcus aureus*. Samples were analysed in accordance with the EC directive Culture technique
					Bathers n = 3796 (85.7%)	Bathers: body immersion for at least 10 minutes including those who had not immersed their head Mean bathing duration was 50 minutes Mean age: 28.33 yrs Age range: 6 months–95 yrs Sex: female 51.2%					
					Non-bathers n = 572 (94.6%)	non-bathers: people who had not visited a beach or swimming pool within 15 days prior to interview and who lived in the same residence as bathers Mean age: 39.05 yrs Age range: 1 yr–95 yrs Sex: female 57.5%					

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Wade, T. J. Sams, E. et al. 2010	Three marine beaches affected by treated sewage 2005: Edgewater Beach in Biloxi, Mississippi 2007: Goddard Beach in Goddard Memorial State Park in West Warwick, Rhode Island, and Fairhope Municipal Beach in Fairhope, Alabama Each beach site was located within 11.25 km or less of a treated sewage discharge outfall from facilities that served populations ≥15,000, generally in compliance with local and federal water quality guidelines	Mississippi and Alabama, US May to September, in 2005 and 2007	Prospectiv e cohort	Extend previous research to three marine beaches in the continental United States where we examine the relationships between swimming-associated illnesses and faecal indicator bacteria determined by alternative rapid methods.	Total number of bathers n = 6,350	Beachgoers of all age groups	All beachgoers were approached for inclusion at the beach on morning of the study. Respondents were ineligible if they had completed the study in the previous 30 days or if there was no adult (≥18 yrs) household member present.	-Water quality -Health outcomes (GI, skin, respiratory, eye, or ear infection)	Data collection for health outcomes followed same protocol as Wade 2006 and Wade 2008. Self-reported by participants who completed an enrolment questionnaire consisting of demographic information, swimming exposures in the previous 2 weeks, and the presence of underlying health conditions. As they left the beach for the day, participants completed a questionnaire to ascertain the extent and duration of their contact with water and other activities during their visit to the beach, such as contact with sand and food consumption. Follow-up phone interviews conducted 10–12 days following the beach visit. GI was defined as any of the following: (1) diarrhoea (three or more loose stools in a 24-hour period); (2) vomiting; (3) nausea and stomach ache; (4) nausea or stomach ache; and (5) interference with regular activities (missed regular activities as a result of the illness). Diarrhoea was also considered as a standalone outcome because it is a commonly used definition of gastroenteritis in population-based surveillance.	Collected two 1 l water samples three times a day (at 8:00 a.m., 11:00 a.m. and 3:00 p.m.) along three transects place 60 m apart perpendicular to the shoreline. Two samples were collected along each transect; one in waist-high water (1 m deep) and one in shin-high water (0.3 m deep). Following collection, samples were placed in coolers and maintained on ice at 1–4°C. At each water sampling time the authors recorded environmental conditions, including air and water temperature, cloud cover, rainfall, wind speed and direction, wave height, number of people (on the beach and in the water), boats, animals (number and type, on the beach and in the water), tide stage, and debris. n = 1,242	Total *Enterococcus* spp. and total Bacteroidales spp. (qPCR, culture). For 2007 samples (Goddard Beach and Fairhope Beacj) authors tested for additional subgroups of *Bacteroides* and *Clostridium* spp. or "*Clostridium perfringens* group" (qPCR, culture), as well as F+(male-specific) coliphage (CLAT assay). One objective of the study was to compare alternative methods; therefore each indicator was enumerated with multiple methods.
					Edgewater Beach n = 1351 (1) body immersion n = 741 (55.1%); (2) head immersion n = 429 (31.9%)	Results not presented by exposure status age: 0–4 yrs 5.7%; 5–11 yrs 11.8%; 12–19 15.2%; 20–34 34.2%; 35 and over 33.1% Race: non-white 40.8%; white 59.2% Sex: male 49.6%; female 50.4%					
					Fairhope Beach n = 2022 (1) body n = 823 (40.8%); (2) head n = 646 (32%)	Age: 0–4 yrs 11.9%; 5–11 yrs 18.7%; 12–19 yrs 10.4%; 20–34 yrs 22.5%; 35 yrs and over 36.6% Race: non-white 34.7%; white 65.3% Sex: male 42.3%; female 57.7%					
					Goddard Beach n = 2977 (1) body n = 1080 (36.4%); (2) head n = 779 (26.2%)	Age: 0–4 yrs 8.1%; 5–11 yrs 11.8%; 12–19 yrs 8.2%; 20–34 yrs 25.1%; 35 yrs and over 46.8% Race: non-white 36.7%; white 63.3% Sex: male 43.2%; female 56.8%					
					Non-swimmers n = NR	Non-swimmers were those who reported no water contact					

Author/year/study name	Type of water/brief description	Study location/country and climate/season	Study design	Study objective (as stated by study authors)	Sample size/details /comparator conditions (if applicable)	Summary of participants/definition of water exposure	Inclusion and exclusion criteria (as reported by study authors)	List of all outcomes evaluated in the study	How was the outcome 'GI' defined/assessed by the study authors?	Methodology (water quality sampling)	Faecal organisms evaluated/method or technique used to measure faecal organisms (e.g. culture, qPCR)
Wade TJ, Converse RR, Sams EA et al. 2013 (abstract only)	Marine beach impacted by urban run-off	South Carolina, US	Prospective cohort	To investigate the association between diarrhoea among swimmers and rain events at a beach in South Carolina impacted by storm water run-off.	n = 11,159 Breakdown of swimmers vs non-swimmers: NR	Beachgoers	Beachgoers	-Water quality -Health outcome (diarrhoea) -The authors also stated that data were collected on 'other symptoms', but these were not specified	Self-reported by participants through a telephone interview 10–12 days after exposure. Diarrhoea was defined as three or more loose stools in a 24 hr period.	NR in abstract	NR in abstract

3.2.2. Fresh water studies

Four studies, presented in six papers, were conducted in a freshwater setting [37-42]. Three of the four freshwater studies investigated the risk of GI among bathers, while the remaining study investigated limited water contact in recreationists, such as boaters and canoeists. None of the studies applied an age restriction to participation.

All four studies were conducted in a temperate climate: three were conducted in Michigan and Ohio, US, and one was conducted in Germany.

For reference, each study is presented separately below and in Table 6. *Please note that the level of detail described below reflects what has been reported by the study authors.*

1. The Chicago Health and Environmental Exposure and Recreation Study (CHEERS) was a prospective cohort among limited water contact (canoers, kayakers, anglers etc.) and no water contact recreators in Illinois, US (temperate climate), from spring to autumn in 2007 to 2009 (August to November 2007, March to October 2008 and April to July 2009) [37 38]. The method for water sampling and evaluation are reported elsewhere in an earlier publication by the study authors for the period April to July 2009 only [43 44]. The level of water exposure (amount swallowed: none, drops, teaspoon or mouthful; and degree of exposure: none, drops, splashed, drenched or submerged) and GI were self-reported in a post-recreation face-to-face interview and by telephone on days 2, 5 and 21 after recreation. Participants reporting GI during follow-up were asked to provide three stool samples for analysis. Participants with GI at baseline were excluded from the analysis. The final cohort for GI had 10,747 participants. Logistic regression models were adjusted for age; gender; race/ethnicity; contact with animals; consumption of shellfish, packaged sandwiches and hamburgers; consumption of raw or undercooked fish, meat and eggs; average bowel movements/day at baseline; contact with person who has GI; diabetes; antibiotic use; antacid use; prone to infection; perceived risk; frequency of recreation at location of enrolment; water recreation during follow-up; eating and hand washing during recreation. Water quality assessment was available for only one time period of the study; this is likely to mask considerable variation in quality between years and seasons, leading to misclassification bias. Authors reported that the comparator groups (exposed vs unexposed) were demographically similar, reducing the impact of selection bias. The final follow-up occurred 21 days after exposure, which may have resulted in recall bias [37 38].
2. Marion et al. (2010) conducted a prospective cohort study of beachgoers at East Fork Lake, Ohio, US (temperate climate), on weekends during the summer of 2009 [39]. A single daily sample was taken near the centre of the beach at a water depth of roughly 0.9 m (3 ft). Samples were collected using a sweeping technique from 1 ft below the water's surface. Samples were enumerated for *E. coli* following EPA Method 1600. In this study, water contact was self-reported in a face-to-face interview on leaving the beach and GI was self-reported in a follow-up telephone interview 8 to 9 days after the beach visit. In total 965 participants from 300 households were included in the analysis. Logistic regression was used to estimate (i) risk of GI among swimmers versus non-swimmers controlled for age, gender, reservoir inflow and household clustering; and (ii) risk of GI and HCGI for swimmers in water with various concentrations of *E. coli* (as a

categorical variable based on quartiles for the *E. coli* distribution) controlled for age, gender, reservoir flow, household clustering, consumption of food at beach and water exposure (swimming or playing). A single daily water sample masks potential variation in water quality throughout the day and variation in different locations of the water. It was not possible, therefore, for the authors to attribute individual exposure status, leading to the potential for misclassification bias. Participants self-selected exposure status and the authors reported that swimmers were on average younger than non-swimmers [39].

3. Two prospective cohort studies from the NEEAR were conducted at beaches affected by point source pollution on Lake Michigan and Lake Erie, US (temperate climate), in the summer of 2003 and 2004 [40 41]. Water samples were collected three times a day, at 08:00 a.m., 11:00 a.m. and 15:00 p.m. on each day of the study along three transects placed 60 meters apart perpendicular to the beach. Samples were taken at waist height depth and shin height depth and analysed for *Enterococcus* spp. using EPA Method 1600 and qPCR. Individual water exposure (immersion of body to waist or higher) was self-reported in a face-to-face interview as participants were leaving the beach, and GI was self-reported in a follow-up telephone interview 10 to 12 days after the beach visit. Respondents who reported experiencing GI in the 3 days prior to the beach visit were excluded from the analysis. In total 20,414 people were included in the analysis. Results are presented for two summary measures (the daily average of all samples and the average of 08:00 a.m. samples) and separated by age category. Logistic regression was used to model incidence of GI in swimmers against *Enterococcus* spp., linear regression was used to estimate attributable risk, and a log-linear model was used to estimate the adjusted cumulative incidence ratio associated with swimming. Models were controlled for age, gender, race, contact with animals, contact with other persons with diarrhoea, frequency of beach visits, chronic GI, digging in sand, beachgoer density, temperature (water and air), rainfall, wind direction, debris, wind speed and wave height. The methods used to collect water quality data appear to have been rigorous within the resource constraints, but the average water quality of the two measures attributed to each bather as the exposure measure is likely to mask within-day variability in the FIO concentrations, leading to potential misclassification bias. There is also the potential for selection bias because individuals self-selected their exposure status; on average swimmers were younger than non-swimmers and more likely to be male [40 41].

4. The randomised control trial conducted by Wiedenmann et al. (2006) was conducted at five freshwater sites (four lakes, one river) in Germany [42]. Water samples were taken every 20 minutes throughout the duration of the study from the centre of each bathing zone (cordoned-off area of approximately 10 m by 20 m). Samples were enumerated for enterococci using culture techniques following International Organization for Standardization protocols. Results are also reported for E. coli, Clostridium perfringens, somatic coliphages, aeromonads and pyocyanine-positive Pseudomonas aeruginosa. Participants were randomly assigned to an exposure status (bather vs non-bather) using block randomisation on the day of the study. Study investigators measured participants' water exposure (length of immersion and number of head immersions). GI was measured 1 week after exposure in a face-to-face interview, and participants underwent a medical examination. A final follow-up questionnaire was conducted 3 weeks after exposure and participant self-reported outcomes. People with pre-existing GI were excluded based on a medical

assessment on the day of the study. A total of 1,981 people were included in the analysis. No Observed Adverse Effect Limits (NOELs) were calculated based on the value at which there was no significant difference in incidence rates between bathers and non-bathers. Confounding factors considered were as follows: age, gender, study location, weather conditions, accidental swallowing of water during trial, previous or additional water contact, previous disease, disease in household members, other household members participating, consumption of prescription drugs, consumption of alcohol and tobacco, travel history, socioeconomic status, leisure activities, risk perception, membership in environmental organisations and background information on recreational water monitoring. The study design reduced the likelihood of misclassification bias: exposure status was randomly assigned and monitored by study investigators to ensure consistency between participants, participants were assigned individual water quality exposure values and GI was confirmed by a doctor [42]

Table 6. Descriptive overview of fresh water studies

Author/year/ study name	Type of water/brief description	Study location/ country and climate/ season	Study design	Study objective (as stated by study authors)	Sample size/details	Summary of participants /definition of water exposure	Inclusion/exclusion criteria (as reported by study authors)	List of all outcomes evaluated in the study	How was the outcome 'GI' defined/assessed by the study authors?	Methodology (water quality sampling)	Faecal organisms evaluated/method or technique used to measure faecal organisms (e.g. culture, qPCR)
Dorevitch et al. 2012a, Dorevitch et al. 2012b The Chicago Health, Environmental Exposure, and Recreation Study (CHEERS)	Effluent-dominated water and general-use waters in Chicago Area Water Ways System; 75% of the flow is wastewater that has undergone secondary treatment but has not been disinfected. Limited contact recreation is permitted, but not swimming. Inland lakes and rivers have been designated by the state for swimming. The inland lakes do not receive wastewater effluent. Lake Michigan receives combined storm and septic flow about once per summer following extreme rain events. Spring to Autumn. August to November 2007, March to October 2008, and April to July 2009	(1) Chicago Area Waterways System (CAWS) and (2) inland lakes, rivers and Lake Michigan beaches in the Chicago area (referred to as General-use water, or GUW), US Temperate	Prospective cohort	To evaluate incidence of illness, severity of illness, associations between water exposure and illness, and risk of illness attributable to limited-contact water recreation on waters dominated by wastewater effluent and on waters approved for general use recreation (such as swimming). Furthermore, to identify associations between water recreation and the presence of bacterial, protozoan or viral pathogens in stool samples among participants.	N = 11,297 those with GI at baseline were removed from final analysis n = 10,747	-	1) Those engaged in limited-contact water recreation (defined as canoeing, fishing, kayaking, motor boating or rowing) at CAWS or GUW (exposed). 2) Those engaged in non-water recreational activities at locations adjacent to the CAWS and GUW locations, including cycling, jogging, rollerblading, team sports and walking (unexposed). People were not eligible if they had engaged in surface-water recreation within the previous 48 hrs, intended to swim during their index recreation event, or would not be available for telephone follow-up. People were not excluded from the study because of unintentional swimming. After completing the day 21 follow-up interview participants were eligible to re-enrol. An individual who had baseline symptoms of a particular outcome was not considered to be at risk for that outcome but was considered at risk for developing other health outcomes.	-Health outcomes (acute gastrointestinal illness (AGI), acute respiratory illness (ARI), ear symptoms, eye symptoms, skin rash)	Self-reported in a face-to-face interview on day of recreation and at 2, 5 and 21 days post-recreation in telephone interview. Participants were asked about exposures, the development of health symptoms and the severity of symptoms since previous interview. AGI defined as (a) three episodes of diarrhoea in 24 hrs; (b) vomiting; (c) nausea with stomach ache; (d) nausea that interferes with regular activities; or (e) stomach that interferes with regular activities (same definition as used for NEEAR study)	NR: the same authors conducted water sampling of the CAWS and GUW for April to July 2009 period only, but this is reported elsewhere.	The same authors have evaluated *E. coli* and enterococci, *Giardia*, adenovirus type F, *Cryptosporidium* and enterovirus for bathing period April to July 2009 (see results comments for references). Three stool samples were collected from individuals who did not have GI at baseline but reported any of the symptoms at one of the follow-up interviews. Samples were tested for *Campylobacter, Salmonella, Shigella, Yersinia, Edwardsiella, Aeromonas, Plesiomonas* (culture), stool viral culture (virus isolation), *Cryptosporidium* and *Giardia* (direct immunofluorescence detection), rotavirus (immunoassay), shigatoxin-producing *E. coli* (PCR), and norovirus (PCR). NR for water sampling; membrane filtration method used for data reported from another study.
					Limited contact recreation in (1) CAW n = 3,966 and (2) GUW n = 3,744	Level of water exposure was assessed in a post-recreation interview by means of amount swallowed (none, drops, teaspoon or mouthful) and degree to which participant got wet (none, drops, splashed, drenched or submerged) 1) CAW: Age: 0–4 0.8%, 5–9 3.7%, 10–17 10.1%, 18–44 y58.7%, 45–64 23.3%, 65+ 3.3% Sex: male 50.0% Activity: 34.2% kayaking, 22.3% canoeing, 16.7% motor boating, 16.1% rowing, 10.7% fishing GUW: Age: 0–4 1.0%, 5–9 4.8%, 10–17 9.9%, 18–44 46.2%, 45–64 34.2%, 65+ 3.9% Sex: male 59.6% Activity: 32.1% canoeing, 32.1% kayaking, 22.9% fishing, 6.7% rowing, 6.2% motor boating					
					Non-water recreation n = 3,587	Age: 0–4 1.7%, 5–9 3.1%, 10–17 5.4%, 18–44 51%, 45–64 32.8%, 65+ 6.0% Sex: male 49.0					

Author/year/ study name	Type of water/brief description	Study location/ country and climate/ season	Study design	Study objective (as stated by study authors)	Sample size/details	Summary of participants /definition of water exposure	Inclusion/exclusion criteria (as reported by study authors)	List of all outcomes evaluated in the study	How was the outcome 'GI' defined/assessed by the study authors?	Methodology (water quality sampling)	Faecal organisms evaluated/method or technique used to measure faecal organisms (e.g. culture, qPCR)
Marion et al. 2010	A public beach (365 m wide) on an inland, human-made, flood control reservoir	East Fork Lake, Ohio, US Summer (May 30 to August 30) 2009	Prospective cohort	To evaluate the effectiveness of *E. coli* as an indicator of GI risk among recreational water users at East Fork Lake, Ohio, US	965 individuals from 300 households Type of bathers: waders, swimmers, those who played in water n = 806 No water contact: n = 159	- Beach visitors with any water contact. Respondents who self-reported wading, swimming or playing in the water Mixed ethnicity, male and female, aged 0–74 yrs No water contact. Respondents who self-reported not to have waded, swum or played in the water Mixed ethnicity, male and female, aged 0–74 yrs	Those visiting the beach at weekends in summer 2009 (May 30 to August 30th)	-Water quality -Health outcomes (GI)	Self-reported in follow-up phone interview 8–9 days after beach visit. GI: any person reporting any of the following symptoms: nausea, stomach ache, diarrhoea or vomiting Highly credible gastrointestinal illness (HCGI): persons reporting either (1) vomiting; (2) diarrhoea and fever; or (3) stomach ache or nausea accompanied with a fever	Samples taken once per day from water approximately 3 ft (0.9 m) deep near the centre of the 365 m beach. Samples were collected in 500 ml sterile containers, by sweeping the bottle or bag approx. 30 cm below the surface of the water. Within-day sample times varied from 10:50 a.m. to 20:25 p.m., although 92% were collected within 4 hrs of the median sample time of 13.52 p.m. N = 26	*E. coli* *E. coli* density was quantified using EPA Method 1603 (a culture method), using autoclaved deionised water as a negative control
Wade et al. 2006; Wade et al. 2008 Part of National Epidemiological and Environmental Assessment of Recreational Water (NEEAR) study	Four freshwater beaches on Lake Michigan and Lake Erie. Beaches selected because they were affected by discharges from waste treatment plants. Water quality at each beach was influenced by point source tributaries that received combined treated sewage treatment discharges from communities with populations of at least 38,000 and with flow rates of over 38 million (10 million gallons) per day. These sewage plants provided secondary treatment as well as disinfection with chlorine and ultraviolet radiation during the summer.	Lake Michigan: (1) Indiana Dunes National Lakeshore, US (2) Silver Beach, near St. Joseph, Michigan, US (3) Washington Park Beach in Michigan City, US Lake Erie: (4) Huntingdon Beach near Cleveland, Ohio, US Holidays and weekends in the summers (June to September) of 2003 and 2004	Prospective cohort	To evaluate qPCR as a faster method to assess recreational water quality and predict swimming-associated illnesses	21,015 interviews; 20,414 people included in analysis Waders n = 3,597 Swimmers n = 10,436 Non-swimmers n = 6,888	Beach visitors Waders: Age: 0–4 9%, 5–10 7%, 11–19 10%, 20–54 66%, 55+ 9% Sex: male 37% Swimmers: (those who reported immersing their body to the waist or higher) Age: 0–4 10%, 5–10 21%, 11–19 20%, 20–54 45%, 55+ 4% Age: 0–4 5%, 5–10 4%, 11–19 12%, 20–54 68%, 55+ 11% Sex: male 40%	Visitors to the beaches during summers of 2003 and 2004. Excluded unaccompanied minors and those who could not speak English or Spanish. Excluded those who were ill within 3 days before their beach visit for the outcome with which they had been afflicted.	- Water quality - Health effects: GI, URI, rash, eye ailments, earache	Health survey was conducted at baseline on day of beach visit; it included swimming and other beach activities, consumption of meat and eggs, chronic illnesses, allergies, acute health symptoms in past 48 hrs, contact with animals. This was followed up 10–12 days later by a telephone interview to ascertain health symptoms experienced since visit. GI diarrhoea (three or more loose stools in a 24 hr period); vomiting; nausea and stomach ache; nausea or stomach ache that affect regular activities (missed time from work or school, or missed other regular activities as a result of illness). Also assessed diarrhoea (three or more loose stools in a 24 hr period) alone and GI with complications (defined as missing regular activities, using medications, or visiting a health provider as a result of a GI symptom.	Water samples were collected three times each day (8:00 a.m., 11:00 a.m. and 3:00 p.m.) along each of three transects perpendicular to the shoreline, one in waist-high water (1 m deep) and one in shin-high water (0.3 m deep).Transects were located at least 60 m apart to include the area used by most beachgoers. At one beach four additional samples were collected because jetties prevented free circulation of water. n = 1359	*Enterococcus* (qPCR & culture), *Bacteroides* (qPCR) (but only *Enterococcus* analysed as there were problems with sensitivity of *Bacteroides* qPCR assay for samples taken in 2004) Two methods: qPCR (results from the qPCR are expressed as qPCR cell equivalents (qPCRCE) per 100 ml volume.) and culture (method 1600) following EPA guidelines

Author/year/ study name	Type of water/brief description	Study location/ country and climate/ season	Study design	Study objective (as stated by study authors)	Sample size/details	Summary of participants /definition of water exposure	Inclusion/exclusion criteria (as reported by study authors)	List of all outcomes evaluated in the study	How was the outcome 'GI' defined/assessed by the study authors?	Methodology (water quality sampling)	Faecal organisms evaluated/method or technique used to measure faecal organisms (e.g. culture, qPCR)
Wiedenmann A, Kruger P, Dietz K, Lopez-Pila J M, Szewzyk R, Botzenhart K, 2006	Five freshwater sites; four sites on lakes, one on a river. All sites had complied with the European standards for at least the previous three bathing seasons. Sources of faecal contamination included treated and untreated municipal sewage, agricultural run-off, and contamination from water fowl. Additional material provided in Annex 1.	Germany (north-east, south-west, and south-east)	Randomised controlled trial	To provide a better scientific basis for the definition of recreational water quality standards.	Total n = 1,981 Bathers: n = 962 (48.56%) Non-bathers n = 1,019 (51.42%)	Bathers; two definitions of exposure: (1) exposed for 10 minutes and (2) had to completely immerse their head at least three times (the number of head immersions was accounted for). Bathing area was split into swimming and non-swimming zones, but it appears that participants conducted the same activity in both zones. Median age: 23 yrs (IQR: 14–39, range: 4–79) Sex: female 49.2% Non-bathers (spent the day on the beach but had no water contact) Median age: 25 yrs (IQR: 15–39, range: 4–89) Sex: female 53.5%	One location was a pilot study and included participants >18 yrs; in the remaining four locations participants >4 yrs were included. Based on health status, as assessed by a doctor, people with pre-existing conditions such as GI were excluded.	Acute febrile respiratory infections, common cold, ear inflammation, skin infections or inflammatory skin reaction, urinary tract infections, GI	1 week after exposure all participants were interviewed and underwent a medical examination of the throat, ears and eyes; 3 weeks, after participants completed a questionnaire. GI was defined as: (a) definition "GE_UK" according to Kay et al. (1994), i.e. diarrhoea and three or more bowel movements per day, or vomiting or nausea and fever or indigestion and fever; (b) "GE_UK-wf", that is GE-UK but without consideration of stool frequency; or (c) "GE_NL-2" according to van Asperen et al. (1998), i.e. diarrhoea or nausea or vomiting or stomach pains	Every 20 mins for the duration of the study, samples were taken from the centre from each of the swimming/non-swimming zones (roped-off bathing areas of approx 10 m by 20 m that were distributed across the beach).	*E. coli* intestinal enterococci *Clostridium, Perfringens,* somatic coliphages, aeromonads, pyocyanine-positive *Pseudomonas aeruginosa* Culture technique. Detailed methodology given in Annex 2.

3.3. Water quality results

Of the 16 included studies, 14 reported on water quality. The remaining two studies assessed water quality, but specific data were not reported. This latter studies were an abstract by Wade et al. (2013) [35] and a pilot study by Fleming et al. (2004), in which the authors commented on water quality in relation to the US Environmental Protection Agency (EPA) quality standards, but the techniques used to measure faecal indicator organisms and the resultant data were not presented [31]. In addition, water quality assessments presented in three of the included studies were not based on data collected as part of the study; two studies used publically available published data [30 36], while the third referenced previous publications [37 38].

The study authors presented water quality results for a number of faecal indicator organisms. The most frequently reported indicator was enterococci, in 12 of the 14 studies. Results for *E. coli* were reported by seven studies; for Marion et al. (2010) it was the only faecal indicator reported. Dwight et al. (2007) reported total coliform counts only.

Of the 11 studies reporting the method of faecal indicator organism enumeration, 10 included culture methods; Wade et al. (2006 & 2008) only reported measuring enterococci using qPCR (although they may have also used culture methods) [40 41]. The total number of water samples taken in a study ranged from 21 to 1,892 at a single study site. Seven of the included studies took multiple samples on each study day [22-25 27 29 32-34 40-42]. The results for mean daily water quality based on enterococci and *E.coli* enumerated by culture methods, unless otherwise stated, are presented in Table 7.

Water quality based on mean cultured enterococci concentrations ranged from 0.19 $\log_{10}$ CFU/100 ml (1.55 CFU/100 ml) to 316 CFU/100 ml for marine water studies and from 2.47 CFU/100 ml to 164 CFU/100 ml for freshwater studies. Results presented by Wade et al. (2006 & 2008) for enterococci in fresh water using qPCR were considerably different from, but not directly comparable to, cultured results (they reported a mean of 770 CE for all beaches). The five[4] studies that present results for enterococci enumerated using both qPCR and culture methods all report greater concentrations using qPCR methods; this may be expected because qPCR includes both viable and non-viable organisms, whereas the culture methods depend on the metabolic state of the organisms. Mean *E. coli* concentrations ranged from 1.6 CFU/100 ml to less than 10^2 $\log_{10}$ CFU/100 ml (100 CFU/100 ml)[5] in marine studies and from 2.76 CFU/100 ml to 678 CFU/100 ml for freshwater studies.

3.3.1. Microbiological water quality in relation to European Bathing Directive quality standards

It was possible to approximate the water quality in eight of the studies (six marine and two freshwater studies) against the European Bathing Directive classifications. Of these estimates, four were based on the

[4] This count does not include Colford et al. (2012), who reported using both culture and qPCR techniques, because results are presented only for culture.

[5] We note that these results are not clear, but they are as reported by the study authors.

90th or 95th percentile [22-24 29 32 33 39 42]. For the remaining studies, estimates were based on the authors' assessment [25 27 36 40 41].

Of the marine studies, one [22-24] could be classified as 'poor' and two as 'excellent' or 'good' [29 32 33]. For the remaining three studies the water quality standard varied. In the study by Harder-Lauridsen et al. (2013), the authors compared health outcomes among triathletes between two consecutive years with different water quality; in the first year water quality was 'poor' and in the following year it was 'good'. In the study by Colford et al. (2012), water quality was dependent on whether the berm was open or closed, with berm open days resulting in 'poor' water quality, while in the study by Arnold et al. (2013) water quality varied by location. We note, however, that in the study by Arnold et al. (2013) the majority (99 per cent) of bathers did not go in the location where water quality would be considered poor.

The water quality in the two freshwater studies was classified 'excellent' [39 42].

While it would be possible to calculate the 90th or 95th percentile for the Wade et al. (2006 & 2008) study, we note that the results were based on qPCR methods, which are likely to overestimate the concentration of enterococci spp. due to the inclusion of nonviable enterococci. As such these results are not directly comparable to the European Bathing quality standards, which are based on culture methods.

In two additional studies, the authors commented on water quality in relation to the US EPA guidelines. In both these studies more than 10 per cent of the samples exceeded 104 CFU/100 ml of enterococci; however, insufficient information was provided to determine if the 10 per cent of samples would exceed the limits specified in the European Bathing Directive or to calculate the 95th or 90th percentile. It was therefore not possible to compare them against the European Bathing Directive [28 31].

Table 7. Water quality results for enterococci and *E.coli* measured by culture techniques as reported by study author and compared with the current European Bathing Directive classification

Author/study	Number of water samples taken	Water quality (enterococci/*E. coli* assessed by culture unless otherwise stated)	Water quality as stated by author	Classification
Marine				
Abdelzaher et al. 2011; Fleisher et al. 2010; Sinigalliano et al. 2010 BEACHES	NR	Enterococci: Mean 71 CFU/100 ml (sd 244) *E. coli*: *NR*	Exceeded regulatory guideline measures in 35% of individual samples measured.	95th percentile: 71 + (1.67 × 244) = 478.48 90th percentile: 71 + (1.28 × 244) = 439.64 'Poor'
Arnold et al. 2013	307	Enterococci: Geometric mean 3 CFU/100 ml Range 0.5 to 1,740 CFU/100 ml *E. coli* (Colilert): Geometric mean 13 Range 0.5 to 1,000	Sites A, B, D and E: 7% of samples means exceeded 35 CFU/100 ml, 4% exceeded statistical threshold value (STV)104 CFU/100 ml. Site C: 95% of samples exceeded STV 104 CFU/100 ml.[a]	Not possible to calculate percentile but likely Sites A, B, D and E 'Good' Site C 'Poor'
Bonilla et al. 2007	288	Presented in a graph and not possible to determine. From visual inspection of graph, we estimate enterococci and *E. coli* were less than 10^2 log CFU/100 ml[b]	NR	Not possible to calculate percentile based on information provided.
Colford et al. 2007 NEEAR	1,892	Enterococci: Geometric mean 29 CFU/100 ml Max 57,940 CFU/100 ml *E. coli*: NR	265/1,897 (13.96%) samples exceeded STV104 CFU/100 ml.	Not possible to calculate percentile based on information provided.

Author/study	Number of water samples taken	Water quality (enterococci/*E. coli* assessed by culture unless otherwise stated)	Water quality as stated by author	Classification
Colford et al. 2012	All days = 481	Enterococci: Range less than 2 to 41,000 CFU/100 ml *E. coli*: NR	17% exceeded STV 104 CFU/100 ml.	Not possible to calculate percentile based on information reported.
	Berm closed = NR	Enterococci: Median 10 CFU/100 ml *E. coli*: NR	5% exceeded STV 104 CFU/100 ml.	Not possible to calculate percentile. 95% less than 104 CFU/100 ml, therefore likely to be 'Excellent' or 'Good'
	Berm open = NR	Enterococci: Median 316 CFU/100 ml *E. coli*: NR	71% exceeded STV 104 CFU/100 ml.	Not possible to calculate percentile. Likely to be 'Poor'
Cordero et al. 2012	Summer = 144	Enterococci: mean 0.19 $\log_{10}$ CFU/100 ml (sd 0.19 $\log_{10}$) (we calculate this as 1.55) *E. coli*: NR	No sample exceeded 35 CFU/100 ml.	Summer: 95th percentile = 0.19 + (1.67 × 0.19) = 0.51 $10^{0.51}$ = 3.24 CFU/100 ml 90th percentile = 0.19 + (1.28 × 0.41) = 0.43 $10^{0.43}$ = 2.69 CFU/100 ml 'Excellent'
	Autumn = 90	Enterococci: mean 0.33 $\log_{10}$ CFU/100 ml (sd 0.41) *E. coli*: NR	No sample exceeded 35 CFU/100 ml.	Autumn: 95th percentile = 0.33 + (1.67 × 0.41) = 1.01 $10^{1.01}$ = 10.23 CFU/100 ml 90th percentile = 0.33 + (1.28 × 0.41) = 0.85 $10^{0.85}$ = 7.08 CFU/100 ml 'Excellent'

Author/study	Number of water samples taken	Water quality (enterococci/*E. coli* assessed by culture unless otherwise stated)	Water quality as stated by author	Classification
Dwight et al. 2004	Data published elsewhere	Mean monthly Total Coliforms: 1998: North Orange County: 2,000 CFU/100 ml in January 12,000 CFU/100 ml in February Santa Cruz: 4,000 CFU/100 ml in February 1999: Similar counts between sites (both below 2,000 CFU/100 ml)	NR	Not possible to calculate percentile based on information provided, but likely to be 'Poor'.
Fleming et al. 2004	NR	Authors state that there was conflicting results between different indicators. Data not shown.	For enterococci on Beach 1 the number of days that levels exceeded STV 104 CFU/100 ml in the dry season was 17% and in the wet season 23%. For faecal coliforms no days exceeded the Florida maximum of 800 CFU/100 ml in either season.	Not possible to calculate percentile based on information provided.
Harder-Lauridsen et al. 2013	Modelled based on data published elsewhere	2010: Enterococci peak 6×10^3 CFU/100 ml *E. coli* range 1.4×10^4 to 2.6×10^4 CFU/100 ml 2011: Enterococci below 200 CFU/100 ml *E. coli* below 500 CFU/100 ml	2010: NR 2011: reported as threshold of EU Bathing Water Directive	Not possible to calculate percentile but likely 2010: 'Poor' 2011: 'Good'

Author/study	Number of water samples taken	Water quality (enterococci/*E. coli* assessed by culture unless otherwise stated)	Water quality as stated by author	Classification
Papastergiou et al. 2011 Greek Bathers Cohort	All beaches = 149 Beach A = 67 Beach B = 61 Beach C = 21	Beach A: Enterococci 5.6 CFU/100 ml *E. coli* geometric mean 2.2 CFU/100 ml Beach B: Enterococci 2.8 CFU/100 ml *E. coli* 1.9 CFU/100 ml Beach C: Enterococci 2.5 CFU/100 ml *E. coli* 1.6 CFU/100 ml	Conformed to EU excellent requirement based on 95th percentile.	Authors reported 95th percentile values. Enterococci: Beach A = 64.6, Beach B = 16.3, Beach C = 10.6 'Excellent' *E. coli:* Beach A = 14.9, Beach B = 10.8, Beach C = 4.7 'Excellent'
Wade et al. 2010 NEEAR	All beaches = 1,234[c] Edgewater Beach = 377 Fairhope Beach = 431 Goddard Beach = 426	Enterococci: Edgewater Beach: Geometric mean 7.2 CFU/100 ml Range 0.1 to 920 CFU/100 ml Fairhope Beach: Geometric mean 21 CFU/100 ml Range 0.1 to 3000 CFU/100 ml Goddard Beach: Geometric mean 3.6 CFU/100 ml Range 0.1 to 960 CFU/100 ml *E. coli*: NR	NR	Not possible to calculate percentile based on information provided.
Wade et al. 2013	NR	NR	NR	Not possible to calculate percentile based on information provided.

Author/study	Number of water samples taken	Water quality (enterococci/*E. coli* assessed by culture unless otherwise stated)	Water quality as stated by author	Classification
Fresh water				
Dorevitch et al. 2012a & 2012b[d]	Based on data published elsewhere	Enterococci: Waterways: geometric mean 164 CFU/100 ml Rivers and Lakes: 70 CFU/100 ml *E. coli:* Waterways: 678 CFU/100 ml Rivers and lakes: 96 CFU/100 ml	NR	Not possible to calculate percentile based on information provided.
Marion et al. 2010	26	Enterococci: NR *E. coli:* Mean 95.1 CFU/100 ml (sd 60.7)	NR	95th percentile 95.1 + (1.67 × 60.7) = 196.47 90th percentile 95.1 + (1.28 × 60.7) = 172.80 'Excellent'
Wade et al. 2006 & 2008 NEEAR	All beaches = 1,359	Enterococci: qPCR mean 770 (sd 10,800) Range 0.05 to 376,000 *E. coli: NR*	25/78 (32%) exceeded 33 CFU/100 ml	Not suitable to calculate based on enumeration method.
	West Beach = 320	Enterococci: Mean 572 (sd 1,280) *E. coli: NR*		
	Huntingdon Beach = 339	Enterococci: Mean 450 (sd 1,300) *E. coli: NR*		
	Silver Beach = 352	Enterococci: Mean 553 (sd 6,260) *E. coli: NR*		
	Washington Park Beach = 348	Enterococci: Mean 1,480 (sd 20,300) *E. coli: NR*		

Author/study	Number of water samples taken	Water quality (enterococci/*E. coli* assessed by culture unless otherwise stated)	Water quality as stated by author	Classification
Wiedenmann et al. 2006	421	Enterococci: Geometric mean 2.47 CFU/100 ml (sd 0.09) Range 3.0 to 1,504 CFU/100 ml *E. coli:* 2.76 CFU/100 ml (sd 0.08) Range 4.7 to 5,344 CFU/100 ml	All sites would have passed European standards; 95% of samples less than 200 CFU/100 ml.	Enterococci: 95th percentile: 2.47 + (1.67 × 0.09) = 2.62 'Excellent' *E. coli:* 95th percentile: 2.7 + (1.67 × 0.08) = 2.58 'Excellent'

NOTE:

[a] EPA guidelines are based on a geometric mean value in a 30-day interval and a statistical threshold value which is equivalent to the 90th percentile.

[b] This is as reported by the study authors and is not clear. Fig. 1 of the Bonilla (2007) paper shows FIO counts from 30 sampling occasions at the three study beaches. *E. coli* ranges from not detected (<1CFU/100 ml) to less than 100 CFU/100 ml and enterococci from not detected (<1CFU/100 ml) to about 100 CFU/100 ml) – enterococci counts were thus higher than *E. coli* counts.

[c] Number presented is for samples tested for enterococci. The total number of water samples tested was 1,242.

[d] Authors only reported water quality for the study period April to July 2009. Data is not reported for August to November 2007 or March to October 2008.

3.4. Health Risks of Bathing

Health outcomes associated with bathing include GI, as well as respiratory, eye and throat infections. In this rapid evidence assessment we considered GI only. The study authors used a range of definitions for GI.

The majority of studies calculated an odds ratio (OR)[6] to estimate the risk of GI associated with exposure to recreational bathing waters. Eleven of the included studies (seven marine and four freshwater) measured the odds of GI among those exposed to bathing water compared with those who were not exposed – i.e. the health risks of bathing compared with not bathing. Thirteen studies investigated the risk of GI among bathers exposed to water of different quality standards – i.e. the health risks of bathing in more or less contaminated water.

Of the 13 studies that investigated the risk of GI among bathers, eight studies (six marine and two freshwater) measured the odds of GI among bathers for each unit increase in FIO concentration – i.e. whether there is evidence of a dose response[7] of increasing risk of illness with decreasing water quality. Additionally, seven studies (four marine and three freshwater studies) investigated evidence for a significant difference in the risk of GI above and below a threshold value; five studies used the US EPA classification standards of geometric mean 35 CFU/100 ml and statistical threshold value of 140 CFU/100 ml.

3.4.1. Risk of gastrointestinal illness among marine water bathers compared with non-bathers

Of the 12 studies conducted in marine waters, seven compared GI in bathers versus non-bathers [23 25 27-29 32 33 35]. All of these studies were conducted in a Mediterranean or subtropical climate: five of these studies were conducted in the US (four in California and one in Florida), one was conducted in Puerto Rico, and one was conducted in Greece. All but one study evaluated bathers of all ages together [23]. The results are summarised in the text below and are presented in Table 8 and Figure 2.

Mediterranean or subtropical type climate

While the majority (4/7) of studies found no significant differences in GI between bathers and non-bathers (of all age groups) at marine beaches [23 27-29], it can be seen from Figure 2 that the overall direction of effect was for an increase in the odds of GI among bathers compared with non-bathers. Two studies reported a decrease in the odds of GI with bathing, although these results were not significant [27 28].

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[6] The odds ratio represents the odds that an outcome will occur given a particular exposure, compared with the odds of the outcome occurring in the absence of that exposure.

[7] The dose response describes how the likelihood and severity of an outcome are related to the concentration of a particular exposure. Typically, as the 'dose' (concentration of FIO) increases, the risk of an outcome (GI) increases.

Three of the studies reported statistically significantly positive findings [25 32 33 35]. In one study, self-reported GI (diarrhoea, vomiting, nausea and stomach cramps; nausea and missed daily activities due to GI; or stomach cramps and missed daily activities due to GI) occurred approximately twice as often in swimmers within 3 days of exposure than in non-swimmers: body immersion adjusted OR 1.90 (95% CI 1.17 to 3.09); head immersion adjusted OR 1.91 (95% CI 1.17 to 3.14); and swallowed water adjusted OR 2.86 (95% CI 1.64 to 4.97) [25]. There was no significant difference in the incidence of GI at 10 days. In their conclusions, the authors emphasised that the 3 days following a beach visit may be the most relevant period for health outcome measurement in recreational water studies[8] [25]. The other studies included in this section, however, do not appear to have specifically evaluated when infection occurred, but, rather, if it occurred within a defined follow-up time period.

In the study conducted in Greece, bathers (defined as people who experienced full body immersion) at Greek beaches experienced a GI (defined as having at least one of the following symptoms: nausea/vomiting, abdominal pain, or diarrhoea) 3.6 times more often than did non-bathers (adjusted OR 3.60 (95% CI 1.28 to 10.13) $p = 0.015$) [32 33]. When GI was more strictly defined (as having two or more of the above symptoms), the result became non-significant at the $p<0.05$ level (adjusted OR 3.16 (95% CI 0.95 to 10.52)). The authors also reported a statistically significant increased risk of GI among bathers at beaches with a higher density of bathers and concluded that beach-bather density should also be considered when conducting a risk assessment [32 33].

In addition, data presented in a conference abstract reported a significant increase in odds of GI (defined as diarrhoea) among bathers (defined as people who experienced body immersion) compared with non-bathers, but only when there was some rainfall in the 24 hours prior to swimming (no rainfall adjusted OR 1.33 (95% CI 0.95 to 1.86), low rainfall adjusted OR 1.55 (95% CI 1.07 to 2.25) and high rainfall adjusted OR 2.14 (95% CI 1.32 to 3.48)) [35].

Interestingly, in two of the studies that reported significant differences, the mean indicator levels of bacteria were low. Arnold et al. (2013) reported that the majority of participants swam in water that would be classified as good or excellent quality, while Papastergiou et al. (2011) reported that all their microbiological water quality test results conformed to the EU ‘excellent’ requirements based on a 95th percentile. For the third study, water quality results were not presented, but we have assumed that with increasing rainfall, the quality of water decreased.

All of the findings, however, need to be considered in the context of the methodology used in each study, and also in the context of the study quality. As reported in Appendix E, the potential for self-selection bias and/or misclassification bias is present in most of the studies that evaluate marine beaches. In the study by Arnold et al. (2013), a site-specific daily-average method to assess water quality was used and subsequently attributed to the swimmers near the sites. A relatively large number of water quality samples were taken at different times of the day ($n = 307$), but no details on the spatial pattern of sampling were provided by the authors. If it was heterogeneous, then attributing the geometric mean water quality to all bathers will miss the key high water quality exposures, which might be over a threshold. We note, however, that the

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[8] It may be that these results imply norovirus infection.

confidence intervals surrounding the odds ratios (for bathers vs non-bathers) were relatively small, indicating a higher level of precision. In contrast, the relatively wide confidence intervals reported in the Papastergiou et al. (2011) study indicate a lower level of precision and hence cause us to have less confidence in the study results. In this latter study a total of 149 water quality samples were taken from the three study beaches (samples taken once per day from seven sampling sites) and 4367 participants were analysed, suggesting that the wide CI was not driven by a small population sample size. Both studies relied on self-reported symptoms of GI and on self-reported level of exposure to water, which may have introduced some error.

Overall, most studies found no significant differences in gastrointestinal illness between bathers and non-bathers (of all age groups) at marine beaches. No firm conclusions can be drawn from this evidence. The results may also reflect systematic differences in the bather and non-bather groups, possibly due to self-selection bias.

Table 8. The risk of gastrointestinal illness among marine bathers compared with non-bathers.

All results are adjusted OR (95% CI) unless otherwise stated. Results that are significant at the p<0.05 level are presented in bold. Where multiple definitions of GI were used the second definition is presented in italics.

Author(s)/ study name	Location, country	Water quality (see Table 7)	Follow-up (days)	No. of participants	Age group	Any water contact vs non-bathers	Body immersion vs non-bathers	Head immersion vs non-bathers	Swallowed water vs non-bathers
Beachgoers									
Fleisher et al. 2010 BEACHES	Florida, US	'Poor' Enterococci: Mean 71 CFU/100 ml (sd 244)	7	1,239	Adults			1.79[a] (0.94, 3.43)	
Arnold et al. 2013	California, US	Sites A, B, D and E 'Good' Site C 'Poor' Enterococci: Geometric mean 3 CFU/100 ml Range 0.5 to 1,740 CFU/100 ml *E. coli* (Colilert): Geometric mean 13 Range 0.5 to 1,000	3–12 (up to 19)	5,674	All ages		**1.90 (1.17, 3.09) (3 days after exposure)**	**1.91 (1.17, 3.14)**	**2.86 (1.64, 4.97)**
							1.14[b] (0.85, 1.54) (10 days after exposure)	1.14 (0.83, 1.56)	1.31 (0.89, 1.94)

Author(s)/ study name	Location, country	Water quality (see Table 7)	Follow-up (days)	No. of participants	Age group	Any water contact vs non-bathers	Body immersion vs non-bathers	Head immersion vs non-bathers	Swallowed water vs non-bathers
Colford et al. 2007 NEEAR	California, US	Enterococci: Geometric mean 29 CFU/100 ml Max 57,940 CFU/100 ml	14	8,797	All ages	0.96[c] (0.68, 1.4) *OR 0.93 (0.49, 1.8)*			1.0 (0.62, 1.7) *1.1 (0.51, 2.5)*
					0–5 yrs	0.86 (0.45, 1.6) *0.75 (0.31, 1.8)*			0.61 (0.25,1.5) *0.74 (0.23, 2.4)*
					6–12 yrs	1.3 (0.56, 3.1) *2.3 (0.28, 18)*			1.7 (0.65, 4.6) *2.8 (0.32, 25)*
					13–30 yrs	OR 0.73 (0.36, 1.4) *0.64 (0.15, 2.7)*			1.3 (0.49, 3.7) *0.92 (0.13, 6.5)*
					>30 yrs	1.4 (0.60, 3.2) *2.1 (0.30, 15)*			0.70 (0.08, 6.3) *3.2 (0.18, 54)*
Colford et al. 2012[d]	California, US	Enterococci: Range less than 2 to 41,000 CFU/100 ml	10–14	9,525	All ages		1.16[c] (0.90, 1.50)	1.25 (0.96, 1.63)	1.32 (0.96, 1.79)

Author(s)/ study name	Location, country	Water quality (see Table 7)	Follow-up (days)	No. of participants	Age group	Any water contact vs non-bathers	Body immersion vs non-bathers	Head immersion vs non-bathers	Swallowed water vs non-bathers
Cordero et al. 2012[e]	Puerto Rico	'Excellent' Summer: Enterococci: mean 0.19 $\log_{10}$ CFU/100 ml (sd 0.19) *E. coli*: NR Autumn: Enterococci: mean 0.33 $\log_{10}$ CFU/100 ml (sd 0.41)	10–12	1,299	All ages	0.88[f] (0.47, 1.63)			
Papastergiou et al. 2011 Greek Bathers Cohort	Greece	'Excellent' Enterococci: mean 0.33 $\log_{10}$ CFU/100 ml (sd 0.41)	10	4,368	All ages		**3.60[g]** **(1.28, 10.13)** *3.16* *(0.95, 10.52)*		
Wade et al. 2013 (abstract only)	California, US	NR	10–12	11,159	All ages		1.33[h] (0.95, 1.86) (when there was no rainfall in the previous 24 hours before swimming) 1.55 (1.07, 2.25) (when there was low rainfall (<1 cm (0.39 inches)) in the previous 24 hours before swimming) 2.14 (01.32, 3.48) (when there was high rainfall (>1 cm (0.39 inches)) in the previous 24 hours before swimming)		

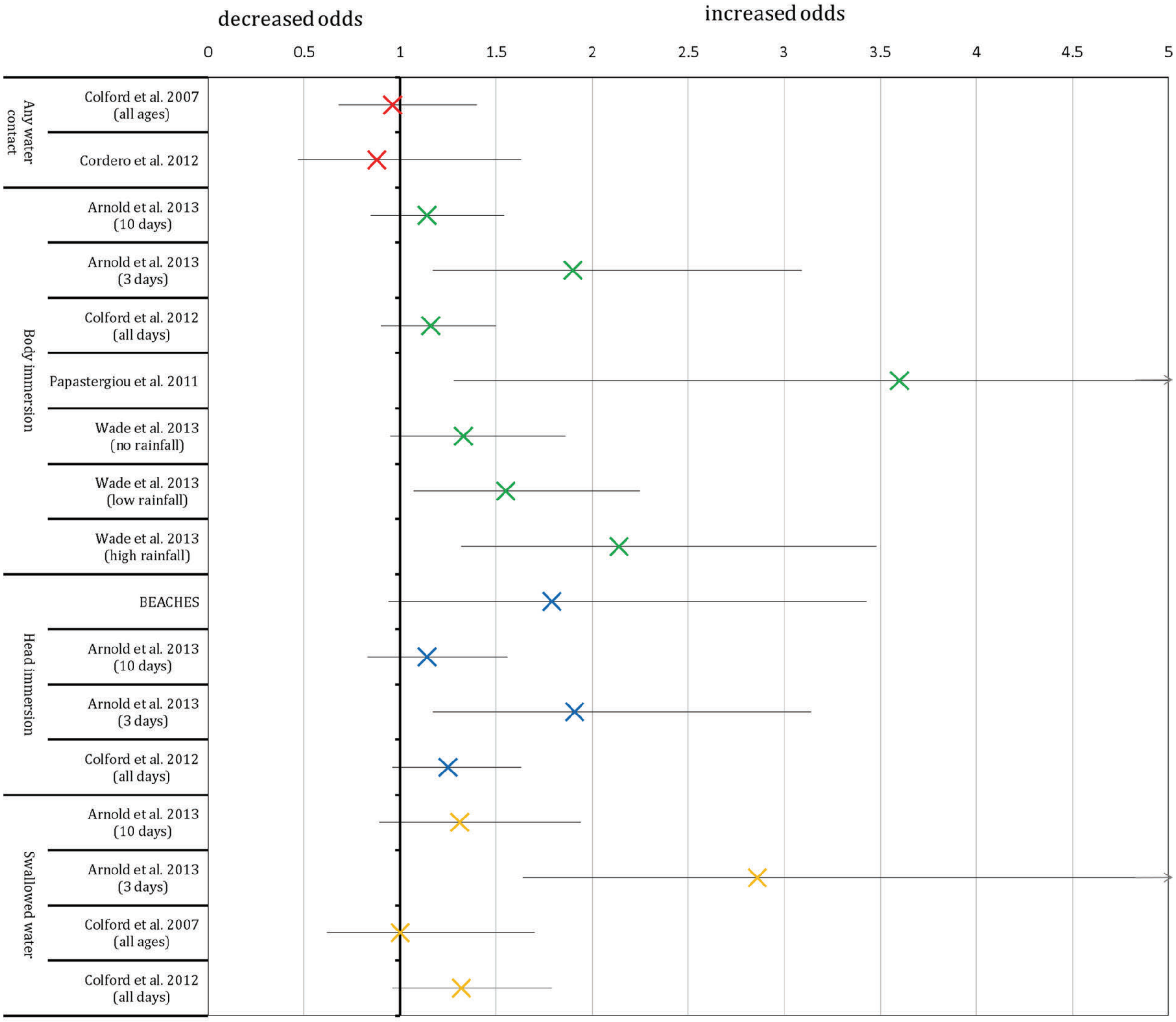
NOTE:
[a] GI was defined as the report of (1) all cases of vomiting or diarrhoea or (2) all reported cases of indigestion or nausea accompanied by a fever; diarrhoea was defined as having three or more runny stools within 24 hours.
[b] GI was defined as diarrhoea (three or more watery stools in 24 hours), vomiting, nausea and stomach cramps, nausea and missed daily activities due to GI, or stomach cramps and missed daily activities due to GI.
[c] GI symptoms included nausea, vomiting diarrhoea, and stomach cramps. Two levels of credible GI were measured: (1) either vomiting; diarrhoea and fever; or cramps and fever (non-italic) and (2) vomiting plus fever (*italics*)
[d] The combined result for all days sampled has been reported here. The authors also reported results for berm open (more polluted) and berm closed days, but no significant results were observed on either berm open or berm closed days.
[e] The figure shown is for both seasons combined; when results are presented separately for each season, the direction of effect is different. In autumn there is an increased risk of GI for bathers compared with non-bathers, while in summer the risk remains decreased. Results are non-significant for both seasons.
[f] GI was defined as any of the following: (1) diarrhoea; having >3 loose stools within a 24-hour period; (2) episodes of vomiting; (3) nausea and stomach ache; (4) stomach ache that affected regular activity; or (5) stomach ache and fever.
[g] GI was defined as nausea/vomiting, abdominal pain, diarrhoea (two or more loose or watery stools in a 24-hour period), fever. Two definitions were used; A (sensitive) required a positive answer to one of the symptoms listed (non-italic) and B (specific) required two or more symptoms *(italics)*. Fever could be included in definition B but not A.
[h] Diarrhoea was defined as three or more loose stools in a 24-hour period.

Without conducting any meta-analysis, the ORs detailed in Table 8 were plotted on a single graph in order to visually explore whether there were any patterns in the results (Figure 2). For those studies that present result for multiple definitions of GI only the first definition is presented (non-italic result in Table 8). For Colford et al. (2007) only the combined result for all ages is presented, as no difference was observed between the different age groups. Likewise for Colford et al. (2012) the combined result for all days sampled is presented, as there was no significant difference in the results between berm open (more polluted) and berm closed days. It therefore does not alter the interpretation of the result. Two results are presented from Arnold et al. (2013) based on the length of follow-up time (GI recorded in 3 and 10 days after exposure). Three results are presented for Wade et al. (2012) based on different environmental conditions.

In total 17 results from 6 studies is presented in Figure 2: two for any water contact, seven for body immersion, four for head immersion and 4 for swallowed water. It can be seen that the majority, 14 out of the 17 results, found that bathers had an increased odds of GI (as variously defined by the study authors) compared with non-bathers, although the results were only significant (i.e. the 95% confidence interval did not cross 1) in three studies (6 out of the 17 individual results).

Interestingly, the only two studies that reported a decrease in odds for bathers compared with non-bathers, both classified bathing exposure as 'any water contact' vs no water contact. However, these results were non-significant.

Figure 2. Odds of GI in marine bathers compared with non-bathers by bather exposure; any water contact (red), body immersion (green), head immersion (blue), swallowed water (yellow).



NOTE: The x-axis represents the OR. An OR greater than 1 represents an increase in risk, while an OR less than 1 represents a decreased risk. The lines either side of the OR represent the 95% confidence interval. The confidence interval indicates how reliable an estimate the presented result is of the true risk of GI for marine bathers, i.e. there is a 95% chance that the true risk lays within the calculated interval. The width of the confidence interval indicates the level of uncertainty associated with the estimate, i.e. the wider the interval the greater the level of uncertainty. For a result to be significant at the $p<0.05$ level, the confidence interval must not straddle 1. The arrows on the right-hand side indicate that the confidence interval extends beyond the graph.

3.4.2. Risk of gastrointestinal illness among marine bathers exposed to water bodies of varying microbiological quality

Two studies measured the odds of GI among individuals who were exposed to water of varying microbiological quality. One was conducted in a Mediterranean type climate (California, US) and the other in a temperate climate (Denmark) [30 36]. The results are presented in Table 9; a summary figure of results is not presented.

Mediterranean type climate

A cross-sectional survey by Dwight et al. (2004) compared the risk of GI among adult surfers in two counties in California; one was considered to be an urban site with highly polluted run-off waters (North Orange County) and the other was considered to be a rural site with less polluted run-off waters (Santa Cruz County). GI occurred 2.3 times more often in the urban site (95% CI 1.27 to 4.25) when there was record-high precipitation (and a large difference in water quality), but the result was not significantly different between counties when there was record-low precipitation (i.e. when there was little difference in water quality estimates). The authors did not take water samples as part of the study, but used data from health care agencies; thus the water quality assessments may not be directly attributable to the study participants. In addition, the surfers reported their symptoms during a three-month period, thus introducing the potential for recall bias, although the authors stated that symptoms were more likely to be underreported (thus pulling the results towards non-significance) [30].

Temperate climate

One retrospective cohort study compared GI among triathletes swimming in non-polluted versus polluted sea water in Denmark [36]. Similar to the study by Dwight et al. (discussed above), the water was polluted by heavy rainfall, resulting in an overflow of sewer discharge outlets during one of the race years. The authors reported that the risk of developing GI was 42 per cent during the polluted year, compared with 8 per cent in the following year, so that swimmers in the polluted water had five times the risk of developing GI than did swimmers in less polluted water (unadjusted relative risk 5.0 (95% CI 4.0 to 6.3)). The authors also found that people who ingested higher doses of sea water had an increased risk of illness. Water samples were not taken as part of this study; data were used from a real-time bathing water quality forecast system. In this study participants completed a questionnaire one month after competing in the race in one year, and one week after the race in the following year. As stated by the authors, it is possible that the difference in length of time till the questionnaire was completed between study years may have contributed to differential recall bias. In addition, the authors reported there was media coverage of the illness during the high pollution year, which could have increased the likelihood of people reporting GI symptoms [36].

Overall, both studies demonstrated that heavy rainfall increased pollution levels in the water and that these higher pollution levels were associated with an increased risk of gastrointestinal illness in swimmers/surfers when compared with those who swam/surfed in less polluted waters. Both studies had methodological limitations, including recall bias.

Table 9. The risk of gastrointestinal illness in marine bathers exposed to more polluted vs less polluted water.

All results are adjusted OR (95% CI) unless otherwise stated. Significant results are presented in bold.

Author(s)	Location, country	Water quality (see Table 7)	Follow-up	No. of participants	Age group	More polluted water vs less polluted water
Surfers						
Dwight et al. 2004	California, US	Mean monthly Total Coliforms: 1998: North Orange County: 2,000 CFU/100 ml in January 12,000 CFU/100 ml in February Santa Cruz: 4,000 CFU/100 ml in February 1999: Similar counts between sites (both below 2,000 CFU/100 ml)	Data on health symptoms were collected for 3 months prior to survey	1,832	Adults	In 1998 (with record-high precipitation), surfers using an urban site with more polluted run-off were more likely to report highly credible gastrointestinal illness than those using a less-polluted rural beach: **2.32 (1.27, 4.25)**[a]. In 1999 (with record-low precipitation), there was no significant differences in GI rates between the two areas: 0.97 (0.62 to 1.51)
Swimmers participating in a triathlon						
Harder-Lauridsen et al. 2013	Copenhagen, Denmark	2010: 'Poor' Enterococci peak 6×10^3 CFU/100 ml *E. coli* range 1.4×10^4 to 2.6×10^4 CFU/100 ml 2011: 'Good' Enterococci below 200 CFU/100 ml *E. coli* below 500 CFU/100 ml	2010: 1 month after competition 2011: 2 weeks after competition	1,769	Adults	2010 vs 2011 (same location, different levels of pollution due to heavy rainfall in 2010) **RR 5.0 (unadjusted) (4.0,6.4)**[b]

NOTE:

[a] Highly credible gastrointestinal illness only reported – defined as vomiting, diarrhoea and fever, or stomach pain and fever.

[b] Two definitions: (1). participants reporting as having suffered diarrhoea or vomiting in the days following the competition; and (2). participants who indicated having had diarrhoea and at least two of the following symptoms: vomiting, stomach cramps, fever, nausea, dizziness or headache (only one result was reported and it is not clear which definition of GI was used in the analysis).

3.4.3. Evidence of a dose-response among marine water bathers

Six studies reported a dose-response analysis (i.e. a relationship between increasing numbers/density of faecal organisms in the water, either as a continuous measure or as a cut-off value, and increased risk of GI) [22-25 27-29 34]. In addition to these studies, Fleming et al. (2004) stated that no significant dose-response relationship was observed in their study, but they did not report any data. The lead author was contacted to obtain additional data, but no response was received. The results are presented in Table 10 and summarised in Figure 3.

It can be seen in Figure 3, that, in general, the results indicate an increase in the odds of GI among bathers for a unit increase in enterococci concentration. However, only one study found any evidence of a significant dose response. Results from the Colford et al. (2012) study show that for a $\log_{10}$ increase in enterococci concentration, the risk of highly credible gastrointestinal illness (HCGI) for bathers increased on days when the berm was open – i.e. when the water quality was considered to be poor [27]. In this study, evidence of a dose response was further supported by the fact that the observed odds increased as level of individual exposure increased: body immersion OR 1.36 (95% CI 0.98, 1.89) (ns), head immersion OR 1.54 (95% CI 1.10, 2.16) and swallowed water OR 1.94 (95% CI 1.23, 3.05). Using the alternative definition of HCGI (diarrhoea or vomiting or nausea and stomach cramps or nausea and missed daily activities due to GI or stomach cramps and missed daily activities due to GI) increased the strength of the observation: body immersion OR 1.70 (95% CI 1.17, 2.46), head immersion 1.87 (95% CI 1.28, 2.72) and swallowed water OR 2.50 (95% CI 1.52, 4.11) [27].

Only one other paper was conducted in 'poor' water quality, but the study authors reported a non-significant increase in the odds of GI among bathers (defined as head immersion) for a $\log_{10}$ increase in enterococci concentration (OR 1.39; 95% CI 0.79 to 2.61) [22-24]. The observed difference in findings could be due to the water quality; even though both would be classified as poor, the mean concentration of enterococci on berm open days in Colford et al. (2012) was 4.5 times more that of in the BEACHES study (316 CFU/100 ml vs 71 CFU/100 ml). The Colford et al. (2012) study further demonstrates that on 'good' water quality days the relationship between increasing enterococci concentration and GI no longer holds.

Four[9] studies compared the odds of GI above and below a threshold value [27 28 32-34]; three of these compared the odds of illness above and below a cut-off point of 35 CFU/100 ml.[10] None found a significant difference in the odds of GI [28 32-34]. In the two studies that compared the difference in odds above and below 140 CFU/100 ml [27 28] (Colford 2007 & 2012), a significant difference was observed in only one [27](Colford et al. 2012). This occurred on days when a berm was open and water quality was 'poor'. The authors used two definitions of GI; for the first definition (HCGI) an effect was only observed when swimmers swallowed water: OR 5.05 (95% CI 1.24, 20.68). For the second definition (diarrhoea) the odds of illness increased with increasing bather exposure: body immersion OR

[9] Colford et al. (2007) considered two cut-off points (i.e. 35 and 140 CFU/100 ml).

[10] A cut-off of 35 CFU/100 ml is based on the US EPA classification; it is equivalent to a 90^{th} percentile of 104 CFU/100 ml. This is likely to equate to an 'excellent' or 'good' classification in the European Bathing Directive.

3.15 (95% CI 1.02, 9.69), head immersion OR 4.20 (95% CI 1.28, 13.75) and swallowed water OR 8.66 (95% CI 1.89, 39.61) [27 28].

We also found some supplementary information on dose response in the included studies. Three studies investigated the impact of swallowing water, but not in relation to water quality [34 36-38] (these results are not presented in Table 10). Wade et al. (2010) reported a significant increase in GI among those who swallowed water with respect to the daily average of enterococci; OR 8.9 (95% CI 2.2, 37) [34]. Harder-Lauridsen et al. (2013) calculated the odds per increasing number of mouthfuls of ingested water in swimmers in 2010 and reported a significant increase in the odds of illness with increasing water consumption: OR 1.19 (95% CI 1.10, 1.28) and OR 1.23 (95% CI 1.11, 1.35), depending on the definition of GI [36]. Dorevitch et al. (2012) reported a significant increase in the odds of GI among bathers who swallowed water compared with those who did not: OR 5.74 (95% CI 2.05, 16.04) [38].

Four studies reported an increase in the risk of GI as length of time spent in water increased [26 30 32-34]. Wade et al. (2010) found a significant increase in the odds of both GI and diarrhoea among bathers who spent more than 90 minutes in the water compared with bathers who spent less than 90 minutes (OR for GI 6.4 (95% CI 1.3, 33) and OR for diarrhoea 7.14 (95% CI 1.4, 37)), based on enterococci concentrations enumerated using qPCR techniques[11] [34]. Papastergiou et al. (2012 & 2011) also found an increase in odds of GI with increasing bathing time, although the results were only significant for one definition of GI; comparing less than 60 minutes with more than 60 minutes spent in water, the odds of GI increases by 1.22 times (95% CI 0.75, 1.99) and 1.94 times (95% CI 1.15, 3.27) [32 33]. Bonilla et al. (2007) demonstrated that for each additional 10 minutes of water exposure the odds of GI increased by 1.009 (95% CI 1.00, 1.02) [26]. Finally, Dwight et al. (2004) reported that the risk increased across almost every symptom measured by an average of 10 per cent for each additional 2.5 hours of water exposure per week, although it is not clear from the results presented if this is true for GI [30].

Seven studies reported results on a dose response. Overall, there was little evidence to suggest that there is a dose response of increasing gastrointestinal illness associated with increasing concentrations of faecal indicator organisms in marine water studies, with only one study reporting a significant dose response on days when water quality would be considered poor. The only RCT conducted in marine water found a non-significant dose response.

There is, however, evidence to suggest that time spent in water is associated with an increased risk of gastrointestinal illness. This finding was observed consistently across the four studies that investigated the impact of length of time, regardless of water quality.

[11] qPCR methods will detect both viable and non-viable enterococci and therefore are likely to overestimate the concentration of indicator organisms, especially in treated water and in particular in water treated through UV disinfection.

Table 10. The risk of gastrointestinal illness associated with bathing in a marine environment for a unit increase in enterococci concentration.

All results are adjusted OR (95% CI) unless otherwise stated. Results that are significant at the p<0.05 level are presented in bold. Where multiple definitions of GI were used the second definition is presented in italics.

Author(s)/ study name	Country	Follow - up (days)	Water quality (see Table 7)	Model details	Dose response				Evidence of a threshold - based on a binary model of enterococci				
					Any water contact	Body immersion	Head immersion	Swallowed water	Any water contact >35 vs <35 CFU/100 ml[a]	Any water contact	Body immersion	Head immersion	Swallowed water
										>140 vs <140 CFU/100 ml[b]			
Abdelzaher. et al. 2011; Sinigalliano et al. 2010 ; Fleisher et al. 2010 BEACHES	US	7	'Poor' mean 71 CFU/100 ml (SD 244)	Log_{10} increase			1.39 (0.74, 2.61)						
Arnold et al. 2013	US	10	Sites A, B, D and E 'Good' Site C 'Poor' Geometric mean 3 CFU/100 ml (range 0.5 to 1,740)	Log_{10} increase		0.94 (0.70, 1.25)	1.06 (0.76, 1.47)	1.19 (0.62, 2.28)					
		3				0.90 (0.57, 1.41)	1.09 (0.68, 1.74)	0.86 (0.42, 1.77)					
Colford et al. 2007 NEEAR	US	14	Geometric mean 29 CFU/100 ml (max 57,940/100 ml)	geometric mean change of 3 ln increase per 100 ml	0.76[c] (0.28, 2.0) *0.97 (0.18, 5.2)*			1.6 (0.25, 1.7) *1.7 (0.009, 31)*	0.74 (0.51, 1.1) *0.69 (0.38, 1.3)*	1.1 (0.73, 1.8) *0.80 (0.37, 1.7)*			

Author(s)/ study name	Country	Follow - up (days)	Water quality (see Table 7)	Model details	Dose response				Evidence of a threshold - based on a binary model of enterococci				
					Any water contact	Body immersion	Head immersion	Swallowed water	Any water contact >35 vs <35 CFU/100 ml[a]	Any water contact	Body immersion	Head immersion	Swallowed water
										>140 vs <140 CFU/100 ml[b]			
Colford et al. 2012	US	10–14	All days range < 2 to 41,000 CFU/100 ml	Log$_{10}$ increase		1.16[d] (0.97, 1.39) ***1.36 (1.09, 1.69)***	1.16 (0.94, 1.45) ***1.35 (1.03, 1.78)***	**1.52 (1.12, 2.06)** ***1.71 (1.19, 2.45)***			0.85 (0.35, 2.11) *1.32 (0.53, 3.30)*	1.17 (0.47, 2.93) *1.85 (0.73, 4.68)*	2.68 (0.90, 7.94) ***3.94 (1.33, 11.66)***
			'Good' Berm closed days median 10 CFU/100 ml			1.08 (0.88, 1.32) *1.20 (0.94, 1.53)*	1.01 (0.79, 1.29) *1.12 (0.83, 1.51)*	1.29 (0.88, 1.88) *OR 1.42 (0.93, 2.18)*			0.22 (0.03, 1.62) *0.32 (0.04, 2.39)*	0.31 (0.04, 2.25) *0.46 (0.06, 3.37)*	0.87 (0.12, 6.17) *1.26 (0.18, 8.95)*
			'Poor' Berm open days Median: 316 CFU/100 ml			1.36 (0.98, 1.89) ***1.70 (1.17, 2.46)***	**1.54 (1.10, 2.16)** ***1.87 (1.28, 2.72)***	**1.94 (1.23, 3.05)** ***2.50 (1.52, 4.11)***			1.71 (0.58, 5.01) ***3.15 (1.02, 9.69)***	2.24 (0.72, 6.99) ***4.20 (1.28, 13.75)***	**5.05 (1.24, 20.68)** ***8.66 (1.89, 39.81)***
Cordero et al. 2012	Puerto Rico	10–12	'Excellent' (a) summer: 0.19 log10 CFU/100 ml (sd 0.19), (b) autumn: 0.33 log10 CFU/100 ml (sd 0.41)	Log$_{10}$ increase		3.59 (0.63, 20.57)							
Papastergiou, et al. 2012 & 2011 Greek Bathers Cohort	Greece	10	'Excellent' Beach a): 5.6 CFU/100 ml Beach b): 2.8 CFU/100 ml Beach c): 2.5 CFU/100 ml						0.68[e] (0.27, 1.76) *0.53 (0.12, 2.22)*				

Author(s)/ study name	Country	Follow - up (days)	Water quality (see Table 7)	Model details	Dose response				Evidence of a threshold - based on a binary model of enterococci				
					Any water contact	Body immersion	Head immersion	Swallowed water	Any water contact >35 vs <35 CFU/100 ml[a]	Any water contact	Body immersion	Head immersion	Swallowed water
										>140 vs <140 CFU/100 ml[b]			
Wade. et al. 2010 NEEAR	US	10–12	Edgewater Beach Geometric mean 7.2 CFU/100 ml (Range 0.1 to 920) Fairhope Beach: 21CFU/100 ml (Range: 0.1-3000) Goddard Beach geometric mean 3.6 CFU/100 ml (Range:0.1-960)	Log_{10} increase		Daily average of samples[f]: All participants: 1.16 (0.84, 1.61) Children under 10: 0.97 (0.54, 1.75)			All participants: 1.2 (0.75, 1.91)				

NOTE:

[a] Based on geometric mean

[b] Based on a statistical threshold value equivalent to 90th percentile

[c] Two definitions of GI: (1) HCGI-1 either vomiting, diarrhoea and fever or cramps and fever (non-italics); and (2) HCGI-2 vomiting plus fever *(italics)*.

[d] Two definitions: (1) HCGI: Diarrhoea or vomiting or nausea and stomach cramps or nausea and missed daily activities due to GI or stomach cramps and missed daily activities due to GI (non-italics); and (2) GI: included nausea, vomiting, diarrhoea (three or more runny stools within 24 hours), stomach ache and abdominal cramping *(italics)*.

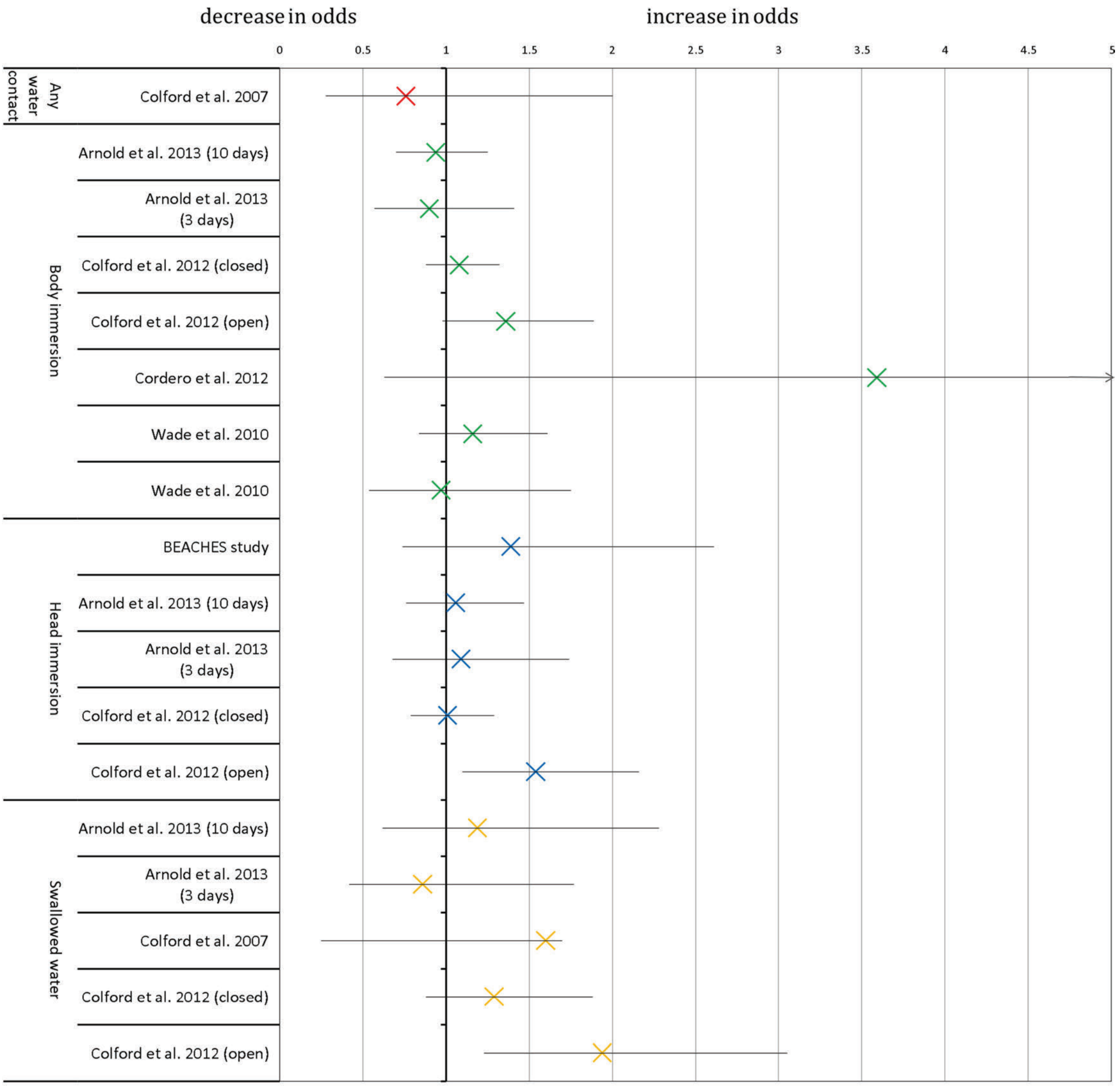
[e] Two definitions: (1) GI sensitive: required a positive answer to one of the symptoms (nausea/vomiting, abdominal pain, diarrhoea (defined as two or more loose or watery stools in a 24-hour period), fever) (non-italics); and (2) GI specific: required two or more symptoms (nausea/vomiting, abdominal pain, diarrhoea (defined as two or more loose or watery stools in a 24-hour period), fever).

[f] Wade et al. (2010) presented results for both a daily average (average of samples taken at 08:00, 11:00. and 15:00) and individual sampling times (08:00 and 11:00), but only daily average is shown here as the interpretation of the results was similar for all sampling times.

A visual plot of the odds of GI associated with increasing enterococci concentration, as detailed in Table 12, is presented in a Figure 3 (no meta-analysis has been conducted). Based on the study authors' primary definition of GI (which may vary between studies), 18 individual results were reported for a dose response within the six studies; one for any water contact, seven body immersion, five head immersion and five swallowed water.

It can be seen that 13 out of 18 results demonstrated an increase in the odds of GI with increasing enterococci concentration in water samples, although only two were statistically significant (i.e. the 95% confidence interval did not include 1), and these results are both from the same study [27]. Furthermore, it appears that with increasing bather exposure i.e. moving vertically down the graph the odds of GI are more frequently greater than 1: any water contact 0/1, body contact 4/7, head immersion 5/5, swallowed water 4/5. This does not, however, take into account the size of the effect or whether the result was significant.

Figure 3. Odds of gastrointestinal illness for a unit increase in enterococci concentration presented separately by bather exposure (dose response): any water contact (red), body immersion (green), head immersion (blue), swallowed water (yellow).



NOTE: Two results are presented from Arnold et al. (2013) based on the length of follow-up time (GI recorded in three and ten days after exposure). Two results are presented for Colford et al. (2012) berm open and berm closed days.

3.4.4. Risk of gastrointestinal illness among fresh water bathers compared to non-bathers

Of the four freshwater studies identified in this review, three compared GI in freshwater bathers versus non-bathers [39-42]. All three studies took place in a temperate climate; two of these were conducted in the USA (Ohio and Michigan) and one was conducted in Germany. The results are presented in Table 11 and summarised in Figure 4.

Temperate climate

All of the studies reported results for all age groups, and one also reported results by age categories [40 41]. All three studies reported a statistically significant increase in the risk of GI among freshwater bathers compared with non-bathers.

The study by Marion et al. (2010) was conducted at an engineered inland lake in the US [39]. The authors reported that GI (defined as any of the following symptoms: nausea, stomach ache, diarrhoea or vomiting) occurred three times more often in people who were bathing (wading, playing or swimming) in the water than in non-swimmers: adjusted OR 3.2 (95% CI 1.1 to 9.0) [39]. In the study by Wade et al. (2006 & 2008), data were collected from four different lake beaches in the US [40 41]. When the data were summarised for all beaches combined, the adjusted risk of GI was 1.44 times higher in swimmers (immersion of their body to the waist or higher) than in non-swimmers (95% CI 1.27 to 1.64). Analysis by age groups demonstrated that this significant finding persisted in almost all age groups. Those 55 years or older were found to have the greatest risk, with older swimmers reporting 2.3 times as many illnesses as non-swimmers (95% CI 1.33 to 3.99). The authors stated that this finding may, however, have been skewed by the low incidence of GI among non-swimmers [40 41]. The third study conducted by Wiedenmann et al. (2006) was conducted at freshwater bathing sites in Germany [42]. These authors also found that swimmers had a significantly increased risk of GI (regardless of the definition used) compared with non-swimmers (see Table 11).

As with the marine studies, two of the studies relied on self-reported symptoms of GI and on self-reported water exposure levels [39-41]. In the Marion et al. (2010) study, only 26 water samples were collected, increasing the risk of misclassification bias [39]. As reported above, the RCT by Wiedenmann et al. (2006) took measures to reduce misclassification and self-selection biases, thus increasing our confidence in their study results [42].

Three studies consistently found differences in gastrointestinal illness outcomes between bathers and non-bathers at freshwater beaches, regardless of the quality of the water at these beaches (which ranged from 'poor' to 'excellent'). When data were evaluated by age group and degree of exposure or by definition of gastrointestinal illness, the results remained significant.

Table 11. The risk of gastrointestinal illness among freshwater bathers compared with non-bathers.

All results are adjusted OR (95% CI) unless otherwise stated. Results that are significant at the p<0.05 level are presented in bold. Where multiple definitions of GI were used the second definition is presented in italics.

Author(s)/ Study	Location, country	Water quality (see Table 7)	Follow-up (days)	No of participants	Age group	Any water contact vs non-bathers	Body immersion vs non-bathers	Head immersion vs non-bathers
Beachgoers								
Marion et al. 2010	Ohio, US	'Excellent' *E. coli* mean 95.1 CFU/100 ml (sd 60.7)	8–9	965	All ages	**3.2**[a] **(1.1, 9.0)**		
Wade et al. 2006; 2008 NEEAR	Ohio and Michigan, US	'Poor' qPCR mean 770 (sd 10,800) Range 0.05 to 376,000)	10–12	20,414	All ages		aCIR: **1.44** **(1.27, 1.64)**	
					≤5 yrs	**aCIR 1.67**[b] **(1.03, 2.69)**		
					≤10 yrs	aCIR: 1.42 (0.99,2.11)		
					11–54 yrs	**aCIR: 1.40** **(1.22, 1.61)**		
					55+ yrs	**aCIR: 2.30** **(1.33, 3.99)**		
		West Beach: qPCR mean 572 (sd 1,280)		2,876	All ages	**aCIR: 1.90** **(1.23, 2.92)** **aOR 1.96** **(1.33, 2.90)**	2.26 (1.51, 3.39)	2.14 (1.41, 3.27)
		Huntington Beach: qPCR mean 450 (sd 1,300)		2,840		**aCIR: 1.39** **(1.03,1.86)** aOR 1.27 (0.97, 1.67)	1.45 (1.06, 1.98)	1.50 (1.06, 2.13)
		Silver Beach: qPCR mean 553 (SD 6260)				**aCIR: 1.43** **(1.18,1.74)**		
		Washington Park beach: qPCR mean 1480 (SD 20,300)				aCIR: 1.32 (0.99,1.74)		

Author(s)/ Study	Location, country	Water quality (see Table 7)	Follow-up (days)	No of participants	Age group	Any water contact vs non-bathers	Body immersion vs non-bathers	Head immersion vs non-bathers
Wiedenmann et al. 2006	Germany	'Excellent' Geometric mean: 2.47 CFU/100 ml (sd 0.09) Range 3.0 to 1,504 CFU/100 ml	7	1,981	All ages	RR: 2.4[c] (1.23, 4.54) *RR 1.9* *(1.20, 3.08* *RR 1.4* *(0.99, 2.06)*		

NOTE:

[a] GI defined as any person reporting any of the following symptoms: nausea, stomach ache, diarrhoea or vomiting

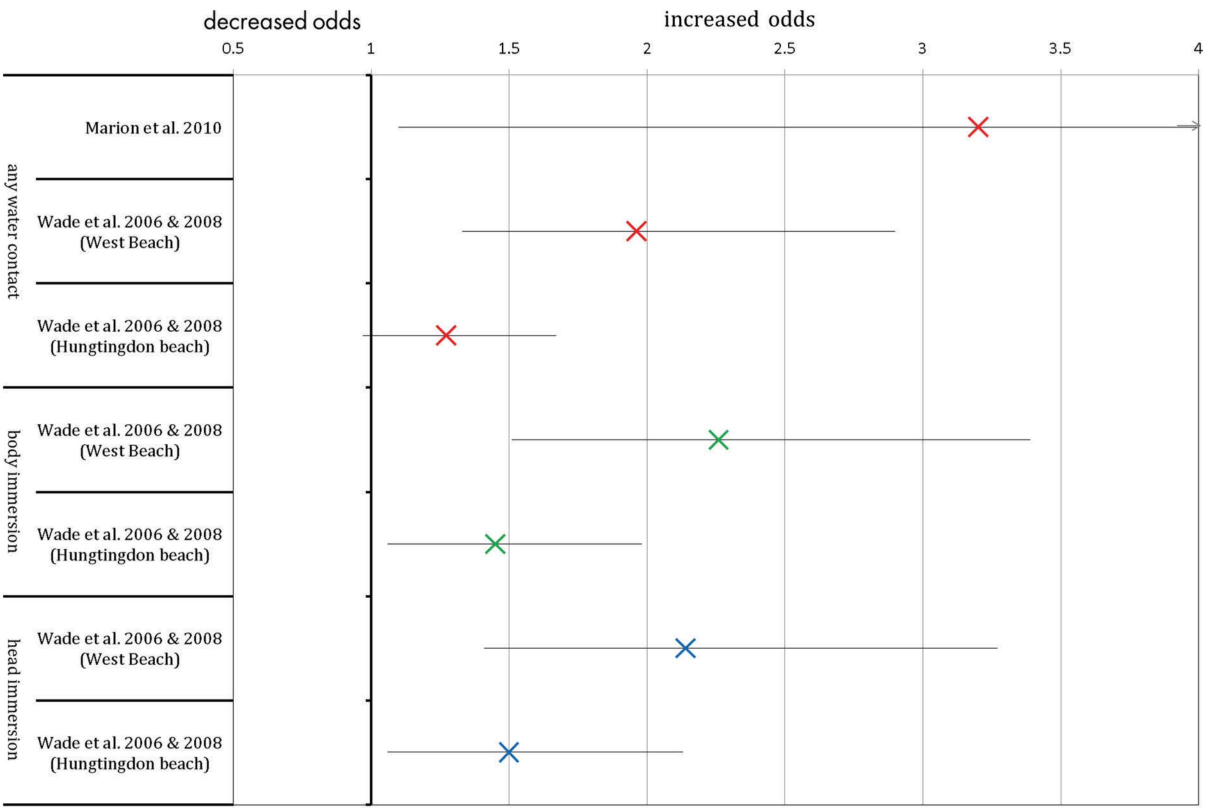
[b] GI was defined as any of the following: (1) diarrhoea (three or more loose stools in a 24-hour period); (2) vomiting; (3) nausea and stomach ache; (4) nausea or stomach ache and interference with regular activities (missed regular activities as a result of the illness).

[c] Three definitions of GI: (1) definition "GE_UK" according to Kay et al. (1994), i.e. diarrhoea and three or more bowel movements per day, or vomiting or nausea and fever or indigestion and fever (non-italics); (2) "GE_UK-wf", that is, GE-UK but without consideration of stool frequency *(italics)*; and (3) "GE_NL-2" according to van Asperen et al. (1998), i.e. diarrhoea or nausea or vomiting or stomach pains *(second italics)*

All results detailed in Table 11, except for Wiedenmann et al. (2006), which is not included because the authors presented the comparative risk of GI as an RR rather than an OR and aCIR results presented by Wade et al. (2006 & 2008), are summarised in Figure 4 (no meta-analysis was conducted). In total seven individual results from two papers were reported: three for any water contact, two for body immersion and two for head immersion.

It can be seen from Figure 4 that all of the results showed that there was an increase in the odds of GI for freshwater bathers compared with non-bathers regardless of bather exposure. Furthermore, for six out of the seven results the 95 per cent confidence interval did not cross 1; hence the results are significant at the $p<0.05$ level.

Figure 4. Odds of GI in fresh water bathers compared to non-bathers by bather exposure; any water contact (red), body immersion (green), head immersion (blue).



Data presented for Wade et al. (2006 & 2008) from West Beach and Huntingdon Beach only.

3.4.5. Risk of gastrointestinal illness among freshwater-recreators compared to non-water contact recreators

One prospective cohort study, set in a temperate climate, evaluated the health risks of limited water recreational contact in a waterways system and in lakes, in rivers and on beaches in the Chicago area in the US [37 38]. The authors found that the odds of GI in recreational water users (e.g. canoeing, fishing, kayaking, motor boating, or rowing) were one and a half times higher than that in non-water recreational users (e.g. cycling, jogging, rollerblading, playing team sports and walking). This finding held in both effluent-dominant waterways (adjusted OR 1.46 (95% CI 1.08 to 1.96)) and general-use waters, including inland lakes and rivers (adjusted OR 1.50 (95% CI 1.09 to 2.07)). The authors also reported no significant difference in GI between recreational water users in waterways compared with general-use waters. The authors also reported that swallowing water was associated with the occurrence of GI. No details regarding the number of water samples were reported in this study, nor do the authors note whether or not water samples were collected near the exposed participants. Participants were included depending on their location of recreation, and exposure to water was self-reported, thus introducing the potential for self-selection bias. Data were however, gathered for a large sample of individuals with limited loss to follow-up (n = 11,297) [37 38]. The results are presented in Table 12; a summary figure of results is not presented.

One study found that the odds of gastrointestinal illness in recreational water users (e.g. those canoeing, fishing, kayaking, motor boating, or rowing) were one and a half times higher than that in non-water recreational users (e.g. those cycling, jogging, rollerblading, playing team sports and walking), in both effluent-dominant waterways and general-use waters, including inland lakes and rivers.

Table 12. Risk of gastrointestinal illness of freshwater recreators compared with (a) non-water contact recreators and (b) freshwater recreators in different water sources (waterways system vs river and lakes).

All results are adjusted OR (95%CI) unless otherwise stated. Results that are significant at the p<0.05 level are presented in bold. A summary figure of results is not presented.

Author(s)	Location, country	Water quality (see Table 7)	Follow-up (days)	No. of participants	Age group	Water recreation vs non-water recreation[a]	Waterways system vs rivers and lakes
Recreational water users (canoeing, fishing, kayaking, motor boating, or rowing)							
Dorevitch et al. 2012a & 2012b[c]	Chicago, Illinois, US	Enterococci: Waterways: geometric mean 164 CFU/100 ml Rivers and lakes: geometric mean 70 CFU/100 ml	0–3	11,297	All ages	Waterways vs non-water recreation: **1.46[b]** **(1.08, 1.96)**	1.02 (0.80, 1.31)
						Rivers and lakes vs non-water recreation: **1.50** **(1.09, 2.07)**	

NOTE:

[a] non-water recreationists includes cyclists, joggers, roller-bladders, team sports and walkers.

[b] GI defined as (a) three episodes of diarrhoea in 24 hrs; (b) vomiting; (c) nausea with stomach ache; (d) nausea that interferes with regular activities, or (e) stomach ache that interferes with regular activities.

[c] The authors concluded that limited-contact recreation, both on effluent-dominated waters and on waters designated for general use, was associated with an elevated risk of gastrointestinal illness

3.4.6. Evidence of a dose response among freshwater bathers

Three out of the four freshwater studies found evidence of a dose response, i.e. increasing risk of illness with increasing FIO density [39-42]. All three of these studies were conducted in a temperate climate, and two of the three studies were conducted in water that would be classified as excellent according to the European Bathing Directive (2006). The study by Wiedenmann et al. (2006) demonstrated a dose response by calculating a threshold value which represents the excess risk of GI to bathers. The results are presented in Table 13; a summary figure of results is not presented.

The study by Marion et al. (2010) was conducted in water that would be classified as excellent by the European Bathing Directive (2006). It demonstrated a positive correlation between GI and increasing *E. coli*, correlation coefficient = 0.47, p-value = 0.03. The strength of the relationship did not increase when the author used a more stringent definition of GI (HCGI), correlation coefficient = 0.45, p-value = 0.03. Water quality was based on a single daily sample; it is therefore likely that bather exposure was subject to misclassification bias [39].

The study by Wade et al. (2006 & 2008) found that for a $\log_{10}$ increase in enterococci (enumerated by qPCR), the odds of GI among bathers increased by 1.29 times (95% CI 1.06, 1.51). However, when the results were analysed separately by age group, the direction of effect remained the same, but the association was significant only for bathers aged 10 years and younger: OR 1.69 (95% CI 1.24, 2.30) [40 41].

All three studies investigated the risk of GI above and below a threshold value [39-42]. Marion et al. (2010) investigated *E. coli* as a categorical variable, Wade et al. (2006 & 2008) compared odds of GI above and below the US EPA classification standard of 35 CFU/100 ml, while Wiedenman et al. (2006) calculated a No Observed Affect Effect Limit (NOAEL).

The study by Marion et al. (2010) compared different categories of *E. coli* density with a baseline value of 0.1 to 3.3 CFU/100 ml. The odds of GI were greater in all categories of *E. coli* density above 3.3 CFU/100 ml, but were only significant when enterococci concentration was greater than 11 CFU/100 ml for HCGI. We noted that the confidence intervals were very wide, suggesting a high level of uncertainty [39].

Wade et al. (2006 & 2008) found an increase in odds for individuals exposed above 35 CFU/100 ml compared with those exposed below, although this observation was not significant at the $p<0.05$ level [40 41]. However, because estimates for enterococci concentration were based on qPCR methods, they are likely to overestimate the number of viable FIOs, so the results are not directly comparable with culture methods.

Wiedenmann et al. (2006) calculated NOAEL values.[12] The NOAEL values estimated for bathers (exposure defined as at least 10 minutes in water and at least three head immersions), not controlling for the number of head immersions, ranged from 21 to 24 CFU/100 ml for enterococci and from 78 to 180

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[12] Bathers exposed to enterococci concentrations above the NOAEL value had a significantly increased risk of GI compared with bathers exposed to concentrations below this value, and bathers exposed below this value did not have an increased risk of illness compared with non-bathers.

CFU/100 ml for *E. coli*, depending on the definition of GI used. When controlling for the number of head immersions, the range of NOAEL values increased to 123 to 145 CFU/100 ml for enterococci and to 1,453 to 2,163 CFU/100 ml for *E. coli.* The authors calculated the relative risk[13] of GI among bathers exposed to FIO above versus below the NOAEL value. The risk of illness was up to 3.6 times greater among those bathers exposed to FIO concentrations above the NOAEL value compared with those exposed to concentrations below that value [42]. The Wiedenmann et al. (2006) study was the only RCT that was conducted in fresh water and the only study of the three to report an individual participant's exposure status.

Three studies conducted in fresh water presented results for a dose response. Overall, there appears to be a significant dose response between faecal indicator organisms and gastrointestinal illness in freshwater bathers; i.e. the risk of illness increases with decreasing water quality.

Evidence of a dose response was observed even in water that would be classified as 'excellent' according to the European Bathing Directive (2006). In the one RCT that was well conducted, evidence of a dose response was observed at enterococci concentrations as low as 21 CFU/100 ml, well below the European Bathing Directive's 'excellent' classification of 200 CFU/100 ml.

[13] The relative risk represents the probability that an exposed individual will develop GI relative to an unexposed individual.

Table 13. The risk of gastrointestinal illness associated with bathing in a freshwater environment for a unit increase in FIO concentration

All results are adjusted OR (95% CI) unless otherwise stated. Results that are significant at the p<0.05 level are presented in bold. Where multiple definitions of GI were used the second definition is presented in italics.

Author(s)/ study	Country	Water quality (see Table 7)	Follow-up (days)	Model details	Dose response any water contact	Threshold	
						>35 vs <35 CFU/100 ml any water contact	Other
Marion et al. 2010	US	'Excellent' *E. coli* mean 95.1 (sd 60.7) CFU/100 ml Range 0 to 1538 CFU/100 ml	8–9	Linear regression	**Correlation coefficient:** **0.467[a] (p = 0.025)** ***0.451 (p = 0.031)***		Model *E. coli* density baseline 0.1–3.3 CFU/100 ml >3.3–11.3 CFU/100 ml: 1.6 (0.07, 37) *3.2* *(0.53, 19)* >11.3–59 CFU/100 ml: 6.0 (0.54, 71) ***7.2*** ***(1.3, 39)*** >59–1551 CFU/100 ml: 3.7 (0.63, 77) ***7.0*** ***(1.5, 32)***

Author(s)/ study	Country	Water quality (see Table 7)	Follow-up (days)	Model details	Dose response any water contact	Threshold	
						>35 vs <35 CFU/100 ml any water contact	Other
Wade et al. 2006 & 2008	US	qPCR: mean (SD): 770 (10,800) range: 0.050 to 376,000	10–12	Log_{10} increase	All: **1.26[b]** **(1.06, 1.51)** ***1.27*** ***(1.04, 1.56)*** ≤10 yrs : **1.69** **(1.24, 2.30)** ***1.60*** ***(1.04, 2.45)*** 11–54 yrs: 1.13 (0.93, 1.39) *1.17* *(0.92, 1.49)* ≥55 years: 1.21 (0.47, 3.09) *0.68* *(0.23, 2.02)*	All: aCIR 1.13 (0.96–1.32) ≤10 yrs: **aCIR 1.32** **(1.00, 1.73)**	

Author(s)/ study	Country	Water quality (see Table 7)	Follow-up (days)	Model details	Dose response any water contact	Threshold	
						>35 vs <35 CFU/100 ml any water contact	Other
Wiedenmann et al. 2006[1]	Germany	'Excellent' geometric mean: 2.47 (SD 0.09) cfu/100 ml *E. coli* geometric mean: 2.76 (SD 0.08) cfu/100 ml	7	No observed adverse effect level			NOAELs calculated without controlling for the number of head immersions: GI: diarrhoea and three or more bowel movements per day, or vomiting or nausea and fever or indigestion and fever Enterococci 24 cfu/100 ml **RR (above vs below NOAEL) 3.2 (1.64, 6.27)** *E. coli* 180 cfu/100 ml **RR 3.55 (1.79, 7.02)** without consideration of stool frequency Enterococci 21/100 ml **RR 2.67 (1.65, 4.32)** *E. coli* 78/100 ml **RR 2.51 (1.55, 4.05)** diarrhoea or nausea or vomiting or stomach pains Enterococci 24 cfu/100 ml **RR 1.9 (1.3, 2.77)** *E. coli* 167 cfu/100 ml **RR 1.96 (1.32, 2.89)**

NOTE:

[a] Two definitions: (1) HCGI: persons reporting either (1) vomiting; (2) diarrhoea and fever; or (3) stomach ache or nausea accompanied with a fever (non-italics); and (2) GI: any person reporting any of the following symptoms: nausea, stomach ache, diarrhoea or vomiting.

[b] Two definitions: (1) GI: diarrhoea (three or more loose stools in a 24-hr period); vomiting; nausea and stomach ache; nausea or stomach ache that affect regular activities (non-italics); and (2) GI with complications: defined as missing regular activities, using medications, or visiting a health provider as a result of a GI symptom *(italics)*.

4. Discussion

This rapid evidence review sought to evaluate the current epidemiological literature (including randomised controlled trials) that examines the relationship between recreational water use (i.e. exposure to marine and fresh recreational waters) and GI.

There is evidence from the general literature that exposure to polluted recreational waters is associated with an increased risk of illness [4 10]. Furthermore, there is some evidence to suggest that this represents a significant public health burden. For example, Dwight et al. (2005) estimated the cost, based on lost income per illness episode and medical costs, of excess illness associated with exposure to two polluted marine beaches in Orange County, California, to be in the region of US$3 million per year [45]. Up-to-date knowledge regarding the relationship between bathing waters and adverse health effects is therefore important for informing policy development, particularly given that there are 14,494 marine bathing waters in the EU and 6,436 inland fresh waters [1].

This rapid evidence review focused on literature which reported on, or measured, faecal indicator organisms (*E. coli* and enterococci) in water and GI. Overall, 21 papers (16 studies) met the inclusion criteria. Of these 16 studies, 12 were conducted in marine waters, of which 11 were conducted in Mediterranean type or subtropical climates, and four studies were conducted in fresh waters, all of which were in temperate climates. Thus, while it is likely that some of the results from the freshwater studies may be directly applicable to the UK, very few of the reported results for marine studies may be directly applicable to the temperate British climate.

4.1. What is the post 2003 evidence for the health risks of recreational bathing in general – and also to specific groups of bathers?

Based on the studies included in our review, there is continuing evidence that bathing in recreational water poses some increased risk of GI to bathers compared with non–water users. However, because only two studies collected data on water quality *and* GI in specific groups of bathers, such as children and the elderly, data on these specific population groups remains limited. Most studies evaluated the risk of bathing in beachgoers of all age groups. Interestingly, our review of studies published since 2003 found that:

- **There appears to be little or no significant difference between GI in bathers compared with non-bathers at marine beaches.** The findings from seven studies suggest that bathing in the marine waters chosen for study (in warmer climates) poses a relatively low additional risk of GI compared with not bathing. This finding was consistently observed in studies with varying water quality.

- **In contrast, there appears to be a consistent and significantly higher risk of GI in bathers compared with non-bathers in freshwater sites in temperate climates (up to 3.2 times higher).** The findings from three studies suggest that bathing at freshwater sites (in a temperate climate) poses a higher risk of GI than not swimming at these sites. This finding was consistently observed in studies with varying water quality.
- **There is some evidence to suggest that increased bather exposure (i.e. head immersion or swallowing water) results in a higher risk of GI, particularly for freshwater bathers.** Four studies included in this review evaluated GI by different levels of bathing exposure (e.g. body immersion, head immersion, or swallowing water) compared with not bathing. The size of the odds of GI between bathers and non-bathers increased as exposure of the bathers increased. This finding was significant in the one freshwater study that evaluated this outcome and in one out of three marine water studies that evaluated this outcome.
- **There is evidence to suggest that an increase in time spent in water is associated with an increase in GI.** Three studies reported an increase in the risk of GI as length of time spent in water increased. One study reported that the odds of GI were more than 6 times greater among bathers who spent more than 90 minutes in the water compared with bathers who spent less than 90 minutes. The other two studies reported a considerably lower increased risk of GI associated with an extended length of time spent in water, and in one of the two studies the relationship was non-significant.
- **There is very little evidence on how the risk of GI varies with age, as most studies only reported a combined result for all participants.** The freshwater study conducted by Wade et al. (2006 & 2008) reported a cumulative incidence ratio for bathers (any water contact) compared with non-bathers stratified by age group. The risk of GI was highest in younger children and older people: bathers aged 5 years or younger reported 1.67 times the number of illnesses as did non-bathers of the same age, bathers aged 11 to 54 reported 1.4 times the number of illnesses and bathers aged 55 years or over reported 2.3 times the number of illnesses. The authors suggested, however, that the small sample sizes preclude the ability to make any conclusions about the youngest age group. Thus, more studies are needed to evaluate/report on the risk of GI in specific age groups, including young children and the elderly.
- **There is a lack of recent studies which have evaluated the risk of GI in recreational water users other than bathers (e.g. in people canoeing, fishing, kayaking, motor boating, or rowing).** Only one such study was identified in this review, and it was conducted in a freshwater setting. The authors of the study reported that the odds of GI were roughly one and a half times greater in recreational water users compared with non-water recreational users (e.g. people cycling, jogging, rollerblading, playing team sports and walking) in both effluent-dominant waterways and general-use waters, including inland lakes and rivers. Again, these statistically significant results add to the evidence base that the incidence of GI is increased among freshwater users compared to non-freshwater users.

4.2. What is the evidence to support the different classification standards outlined in the European Bathing Directive?

To evaluate current bathing indicator standards, this review considered studies which examined a dose response, i.e. a relationship between increasing numbers/density of faecal organisms in the water, either as a continuous measure or as a cut-off value, and increased risk of GI. We also considered studies that reported the risk of GI in waters with differing pollution levels. This evidence was required to investigate the relationship between the concentration of FIOs in water and GI and to infer whether or not the literature supports the European Bathing Directive (2006) boundaries. Our review of studies published from 2003 onwards found that:

- **There is little evidence for a significant dose response between faecal indicator organisms and GI in marine water.** Only one out of six of the included studies that reported on dose response found a significant relationship between the observed increase in $\log_{10}$ enterococci concentration and an increased risk of GI [27]. Four studies also compared the odds of GI above and below a threshold value (e.g. above and below a cut-off point of either 35 CFU/100 ml or 140 CFU/100 ml). Again, the same study as reported above found a significant difference in the odds of GI [27]. This difference was only found on days when water quality was poor, as indexed by enterococci (median 316 CFU/100 ml). Only one other study had 'poor' water quality. This study found a non-significant increase in GI, but the water quality was 4.5 times less contaminated than in the above study. These findings cannot be used to confirm or disprove that a statistically significant increase of GI occurs in marine waters with 'poor' quality as defined by the European Bathing Directive (2006) i.e. 90th percentile less than 185 enterococci per 100 ml. It is therefore unclear whether these current boundaries are supported.
- **There appears to be a significant dose response between faecal indicator organisms and GI in fresh water.** Three of the freshwater studies reported on a dose response. Two of the studies reported a dose response for a unit decrease in water quality, and both were statistically significant. One of these studies was conducted in water that would be classified as 'excellent' and one was conducted in water that would be classified as 'poor' according to the European Bathing Directive (2006). All three studies investigated the risk of GI above and below a threshold value, although these thresholds varied. One study, conducted in 'excellent' quality water, calculated a No Observed Affect Effect Limit (NOAEL) and found that the risk of GI was up to three and a half times greater among bathers even when they had been exposed to low concentrations of enterococci. Thus, if there is a statistically significant elevation in illness following exposure to water classified as 'excellent' by the European Bathing Directive criteria (2006), this current standard may need further examination.
- **Very high levels of pollution due to heavy rainfall and urban run-off or sewage contamination are associated with increased GI.** Two marine studies were identified that compared GI in surfers or swimmers who were exposed to 'more polluted' water versus 'less polluted' water, and both reported significantly higher odds of GI after exposure to more polluted water. In the one study, pollution reached 6×10^3 enterococci per 100 ml [36]; in the other study, mean monthly total coliform counts up to 12,000 per 100 ml were reported [30]. Total coliforms were not included in the revised Bathing Water Directive (2006, Annex 1) criteria;

however, associated levels of enterococci exceeding current EU standards would be expected in waters exhibiting this concentration of total coliform bacteria. We note, however, that in the latter study, 'less polluted' water had a mean total coliform count of 4,000 CFU/100 ml – which would also be likely to be classed as 'poor' according to the European Bathing Directive (2006). While it is hard to make any conclusions from these observational studies, their results demonstrate the significant impact of high levels of microbial contamination on GI in marine water settings.

4.3. Limitations of studies/evidence base

This rapid evidence assessment followed a systematic review process, and was only limited by searching for published studies from 2003 onwards. At least two reviewers were involved in each stage of the review process, while a third reviewer checked any decisions, thus limiting the potential for reviewer error and bias. There were, however, a number of methodological limitations within and between the available studies, including self-selection (i.e. participants select which group they belong to) and misclassification (i.e. measures of water quality may not be appropriately attributed to bathers). Both problems will produce bias in the findings, so that it is difficult to make firm conclusions from this evidence. Moreover, the many differences in the methods used may have an impact on the results, leading to both over- and underestimation of health effects. For example, some of the included studies reported results using more and less restrictive case definitions of GI, and the attribution of water quality 'exposure' was very different among studies. Clear patterns in the results should not, therefore, be implied. The exact quantification of the impacts of these between-study protocol differences is very difficult and beyond the scope of this review.

In addition, the post-exposure follow-up time varied from 2 to 21 days, with the majority of studies using a longer follow-up time (10 days or more). While the longer follow-up time has the advantage of capturing diseases with a longer incubation period, such as cryptosporidiosis, evidence from a number of the included studies suggests that risk of GI was highest in the days immediately following exposure. For example, Dorevitch et al. (2012) analysed the risk of GI in different time windows and found that the odds of GI decreased as length of follow-up time increased (authors considered GI 0–2 days, 0–4 days and 0–5 days after exposure). This observation is corroborated by Colford et al. (2012), who demonstrated a peak in diarrhoea cases among swimmers compared with non-swimmers in the two days following water exposure. Beyond two days, the incidences of GI were similar between swimmers and non-swimmers. Finally, Wiedenmann et al. (2006) reported that no additional disease information was captured by extending the length of follow up-time from 7 to 21 days. An additional concern is that studies that acquired data after longer post-exposure periods might be more susceptible to recall bias.

The method of collecting water samples also varied. Ten studies conducted and reported a water sampling method; these varied from a single daily sample [28 32 33] up to samples taken every 20 minutes [42]. In addition, different studies adopted different sampling strategies relative to the bather location. Only one study (Wiedenmann, 2006) based its analysis on individual water samples collected close to the bathers, which were then used to define the individuals' exposure status [42]. The use of ecological exposure (i.e. a few samples used to characterise a relatively large area of water used by many bathers) by the remaining studies increases the chance of misclassification bias. This in turn will reduce the slope of any putative dose-response relationship and make it less likely that a significant dose-response relationship between FIO concentration and GI will be identified. More studies are needed that collect adequate numbers of water samples at the same location as the bathers to ensure that a true estimate of water quality can be attributed to each bather. Without reliable measures of water quality, many published results may be of limited value to the policy community responsible for regulatory standards design.

The reported bathing water concentration of cultured enterococci was positively skewed: 11 out of 24 study sites[14] (both marine and freshwater) reported mean cultured enterococci concentrations of less than 10 CFU/100 ml, while only 5 sites had mean cultured enterococci concentrations over 150 CFU/100 ml. We estimate that the majority of study sites (13/17) would be classified as 'excellent' or 'good' using the criteria published in the Bathing Water Directive (2006). The positive skew and limited variation in water quality among studies reduces our ability to identify credible threshold values beyond which there is a significant risk of GI. In particular, none of the included studies were conducted in water that would be classified as 'sufficient' (i.e. fresh water: enterococci 330 CFU/100 ml, *E. coli* 900 CFU/100 ml; marine waters: enterococci 185 CFU/100 ml, *E. coli* 500 CFU/100 ml). Thus, future studies are needed to evaluate the true impact on health of moderate to poor quality water, particularly around concentrations that would be classified as 'sufficient' according to the current directive. However, ethical considerations will constrain the implementation of such investigations. Furthermore, the precision of microbial 'exposure' data at these low levels may be poor due to censored (less than values) data, low numerical values for plate counts and single bacterial enumerations for each sample – in contrast to the triplicate enumerations which were used in the original UK epidemiological studies on which the WHO (2003) Guidelines and EU BWD (2006) criteria are based.

These are examples of some of the limitations of the included studies; there are likely other additional issues that need to be considered, but these are beyond the scope of this review. For example, in this review we primarily reported data on *E. coli* and enterococci, which were measured using culture methods. Other methods frequently reported in the literature include qPCR. Continuing developments in microbiological monitoring are likely to cause difficulty in assessing the relevance of the work of different research groups unless comparability, precision and reproducibility of new microbial methods can be demonstrated.

4.4. Conclusions

Overall, it is difficult to draw any firm conclusions from this evidence because of the heterogeneity of study protocols and methodological limitations, including the possibility of self-selection and misclassification biases. Thus, the various results presented by the study authors could be an artefact of the range of methods used. Moreover, there was limited variation in water quality among the studies. In particular, few studies were conducted in 'poor' water quality and none were conducted in 'sufficient' quality water. This provides a limited evidence base on which to assess the classification standards.

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[14] Studies included multiple study sites; each site has been included as reported in Table 8, Appendix D.

However, two RCTs identified in this rapid evidence review were well conducted, and their results are likely to be reliable (Fleisher et al. 2010; Wiedenmann et al. 2006). Fleisher et al. (2010) conducted a study in 'poor' quality marine water. The authors found that bathers were almost two times more likely to report an episode of GI after swimming at a Florida, US (semi-tropical), beach compared with non-bathers, but the results were not significant. We note, however, that this study also evaluated other illnesses, and the authors concluded that bathers may be at increased risk of skin illnesses relative to non-bathers. The Wiedenmann et al. (2006) study was conducted in 'excellent' quality freshwater sites in Germany (temperate climate). This study found that the crude relative risk of GI was, significantly, more than two times greater in bathers compared with non-bathers. This increased to more than three and half times when bathers who were exposed to a (defined) higher level of enterococci concentration were compared with non-bathers.

With the methodological limitations of all of the included studies in mind, the following general conclusions may be made:

- Based on 16 studies published since 2003, there appears to be a consistent significant relationship between faecal indicator organisms (as a measure of water quality) and GI in freshwater studies, but not in marine water studies.
- Given an apparent lack of a relationship between GI and water quality levels meeting different boundaries, it is unclear whether the boundaries of the 2006/7/EC Bathing Waters Directive are supported by studies published in the post-2003 period.
- We suggest that more UK epidemiological evidence is needed to disprove or confirm the original work used to derive these boundaries for marine waters.

4.5. Research recommendations

More research is needed to:

- Confirm that the risk of GI is higher in bathers than non-bathers in fresh water, particularly in fresh water considered to be of 'excellent' quality (according to the Directive);
- Assess the apparent lack of relationship between enterococci concentrations and GI in marine waters;
- Evaluate the risk of GI by exposure condition (e.g. by wading, full body immersion, head immersion, swallowing water), particularly in fresh water;
- Evaluate the relationship between faecal indicator organisms and GI in different age groups – in both marine and fresh waters; and
- Evaluate, where ethically possible, the risk of GI in waters of varying water quality (most studies included in this review had water quality that was classified as 'excellent' or 'good').

Randomised controlled study designs (for an example, see the CONSORT statement at www.consort-statement.org) are needed in UK fresh and marine waters to minimise self-selection bias – i.e. designs that attribute exposure more precisely, ideally by assigning a unique exposure value to each bather using multiple FIO enumerations to reduce the imprecision associated with single enumeration values used to define exposure. These study designs also need to be adequately powered, i.e. to facilitate:

- Bather versus non-bather comparisons;
- Low versus high exposure comparisons within the bather group, ideally leading to credible dose-response relationships; and
- Inter-age group comparisons.

Clear, consistent definitions of GI are required to facilitate comparisons between past and future studies. Study specifications by commissioning agencies should include a well-defined and accepted measure of GI – and data on GI should be collected at multiple polling dates after exposure to pick up rapidly presenting viral infection (e.g. that caused by norovirus) and more slowly presenting gastrointestinal illnesses (such as cryptosporidiosis).

Future studies could usefully define comparability between different microbiological tests through the application of, for example, both membrane filtration and most probable number culture methods and, perhaps, qPCR enumeration. This would facilitate better empirically based inter-study comparisons.

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6. Koay TK, Nirmal S, Noitie L, Tan E. An epidemiological investigation of an outbreak of leptospirosis associated with swimming, Beaufort, Sabah. The Medical journal of Malaysia. 2004 Oct;59(4):455-9. PubMed PMID: 15779577. Epub 2005/03/23. Eng.
7. Sartorius B, Andersson Y, Velicko I, De Jong B, Lofdahl M, Hedlund KO, et al. Outbreak of norovirus in Vastra Gotaland associated with recreational activities at two lakes during August 2004. Scandinavian journal of infectious diseases. 2007;39(4):323-31. PubMed PMID: 17454896. Epub 2007/04/25. Eng.
8. Schets FM, AM DERH, Havelaar AH. Disease outbreaks associated with untreated recreational water use. Epidemiology and infection. 2010 Nov 10:1-12. PubMed PMID: 21062530. Epub 2010/11/11. Eng

Appendix B: Search Strategy

Table 14. List of databases and resources searched

Database	Interface
PubMed	PubMed
EMBASE	Elsevier
Cochrane Database of Systematic Reviews (CDSR)	The Cochrane Library (Wiley)
Cochrane Central Register of Controlled Trials (CENTRAL)	The Cochrane Library (Wiley)
Science Citation Index (SCI)	Web of Science
LILACS	http://lilacs.bvsalud.org/en/
Conference Proceedings Citation Index – Science (CPCI-S)	Web of Science
OAISTER	http://oaister.worldcat.org/
Green File	EBSCO
OpenGrey	http://www.opengrey.eu/
Grey Literature Report (NYAM)	http://www.greylit.org/

Textbox 1. Complete list of search terms used in PubMed

(Lake or lakes or Ocean OR oceans OR sea OR seas OR river OR rivers OR pond OR ponds OR reservoir OR reservoirs OR estuary OR estuaries OR estuarine OR stream OR streams OR creek OR creeks OR "water" OR "waters" OR saltwater OR bay OR bays OR inlet OR inlets OR seawater OR reef OR freshwater OR Lochs OR brackish OR coast OR coastal OR "marine water" OR "marine waters" OR recreational OR bathing beaches [MeSH]

AND

Swimmer OR swimming OR swimmers OR bathe OR bather OR bathers OR bathing OR "scuba diver" OR "scuba divers" OR snorkeler OR snorkelers OR snorkeling OR boater OR boaters OR canoeist OR Canoeists OR canoeing OR angler OR anglers OR surfer OR surfers OR surfing OR kayaker OR kayakers OR kayaking OR windsurf* OR paddle OR paddling OR windsurfer OR windsurfing

AND

Enterococci OR Enterococcus OR Streptococcus OR Gastroenteritis OR "faecal indicator" OR "fecal indicator" OR "Fecal coliform" OR "faecal coliform" OR streptococci OR "marine phytoplankton" OR pollution OR pollutant OR pollutants OR "thermotolerant coliform" OR "e coli" OR "e. coli" OR ecoli OR "Escherichia coli" OR microbial OR microbials OR sewage OR "water quality" OR "health risks")

AND

((humans[mh] OR premedline OR "inprocess"[sb] OR publisher[sb]))

OR

"Bathing Water Directive" OR "bathing water standards" OR "bathing water standard" OR ("bathing water"[Title/Abstract] AND "guidance"[Title/Abstract]) OR ("recreational water"[Title/Abstract] AND ("standards"[Title/Abstract] OR "guidance"[Title/Abstract]))

AND NOT

"swimming pool" OR "water park" OR "swimming pools" OR "water parks" OR "drinking water" OR "municipal water" OR "fish" OR "fishes" OR "fisheries" OR "fishery"

For those without the ability to limit the search to human subjects, we added additional terms to "AND NOT" such as frog, minnow, crustacean, etc

Appendix C: Quality Assessment

Table 15. Quality assessment of randomised controlled trials (RCTs) adapted from CRD (2009).

Question
Was randomisation carried out appropriately?
How was 'treatment allocation' defined (e.g. water exposure through to microbial water quality encountered)?
Was the concealment of treatment allocation adequate?
Were the groups similar at the outset of the study in terms of prognostic factors, for example, severity of disease?
Were the care providers, participants and outcome assessors blind to treatment allocation? If any of these people were not blinded, what might be the likely impact on the risk of bias (for each outcome)?
Were there any unexpected imbalances in drop-outs between groups? If so, were they explained or adjusted for?
Is there any evidence to suggest that the authors measured more outcomes than they reported?
Did the analysis include an intention-to-treat analysis? If so, was this appropriate and were appropriate methods used to account for missing data?
Where appropriate, we will also consider:
Was the effects of bias examined in the bather and non-bather cohorts?

Table 16. Quality assessment of non-randomised trials adapted from Newcastle Ottawa quality assessment scale

Note: A study can be awarded a maximum of one star for each numbered item within the Selection and Exposure categories. A maximum of two stars can be given for Comparability.

CASE CONTROL STUDIES	
Selection	
1) Is the case definition adequate?	a) yes, with independent validation b) yes, eg record linkage or based on self reports c) no description
2) Representativeness of the cases	a) consecutive or obviously representative series of cases b) potential for selection biases or not stated
3) Selection of Controls	a) community controls b) hospital controls c) no description
4) Definition of Controls	a) no history of disease (endpoint) b) no description of source
Comparability	
1) Comparability of cases and controls on the basis of the design or analysis	a) study controls for _______________ (Select the most important factor.) b) study controls for any additional factor (This criteria could be modified to indicate specific control for a second important factor.)
Exposure	
1) Ascertainment of exposure	a) secure record (eg surgical records) b) structured interview where blind to case/control status c) interview not blinded to case/control status d) written self report or medical record only e) no description
2) Same method of ascertainment for cases and controls	a) yes b) no
3) Non-Response rate	a) same rate for both groups b) non respondents described c) rate different and no designation

COHORT STUDIES	
Selection	
1) Representativeness of the exposed cohort	a) truly representative of the average ______________ (describe) in the community b) somewhat representative of the average _____________ in the community c) selected group of users eg nurses, volunteers d) no description of the derivation of the cohort
2) Selection of the non exposed cohort	a) drawn from the same community as the exposed cohort b) drawn from a different source c) no description of the derivation of the non exposed cohort
3) Ascertainment of exposure	a) secure record (eg surgical records) b) structured interview c) written self report d) no description
4) Demonstration that outcome of interest was not present at start of study	a) yes b) no
Comparability	
1) Comparability of cohorts on the basis of the design or analysis	a) study controls for ____________ (select the most important factor) b) study controls for any additional factor (This criteria could be modified to indicate specific control for a second important factor.)
Outcome	
1) Assessment of outcome	a) independent blind assessment b) record linkage c) self report d) no description
2) Was follow-up long enough for outcomes to occur	a) yes (select an adequate follow up period for outcome of interest) b) no
3) Adequacy of follow up of cohorts	a) complete follow up - all subjects accounted for b) subjects lost to follow up unlikely to introduce bias - small number lost - > ____ % (select an adequate %) follow up, or description provided of those lost) c) follow up rate < ____% (select an adequate %) and no description of those lost d) no statement

Appendix D: List of included/excluded studies, with reasons

Reference		Reason for exclusion
Abdelzaher AM, Wright ME, Ortega C, Hasan AR, Shibata T, Solo-Gabriele HM, et al. Daily measures of microbes and human health at a non-point source marine beach. Journal of water and health. 2011; 9(3):443-57.	I	Included
Abdelzaher AM, Wright ME, Ortega C, Solo-Gabriele HM, Miller G, Elmir S, et al. Presence of pathogens and indicator microbes at a non-point source subtropical recreational marine beach. Applied and environmental microbiology. 2010; 76(3):724-32.	E	This study examined the efficacy of qPCR compared to membrane filtration techniques; no health outcome was measured.
Alm EW, Burke J, Spain A. Fecal indicator bacteria are abundant in wet sand at freshwater beaches. Water research. 2003; 37(16):3978-82.	E	This study examined at the potential of sand to harbour FIO, and how concentrations compared with sea water; no health outcome was reported.
An W, Zhang D, Xiao S, Yu J, Yang M. Quantitative health risk assessment of Cryptosporidium in rivers of southern China based on continuous monitoring. Environmental science & technology. 2011; 45(11):4951-8.	E	This was a modelling study that evaluated cryptosporidium. The setting was in southern China and considered to be of minimal European relevance.
Arnold BF, Schiff KC, Griffith JF, Gruber JS, Yau V, Wright CC, et al. Swimmer illness associated with marine water exposure and water quality indicators: impact of widely used assumptions. Epidemiology (Cambridge, Mass). 2013; 24(6):845-53.	I	Included
Bienen L. The real cost of marine pollution. Frontiers in Ecology & the Environment. 2005; 3(5):236-.	E	Summary of paper published by Dwight (2004) [included]; investigated cost per illness.
Bonilla TD, Nowosielski K, Cuvelier M, Hartz A, Green M, Esiobu N, et al. Prevalence and distribution of fecal indicator organisms in South Florida beach sand and preliminary assessment of health effects associated with beach sand exposure. Marine pollution bulletin. 2007; 54(9):1472-82.	I	Included

Reference		Reason for exclusion
Bradley G, Hancock C. Increased risk of non-seasonal and body immersion recreational marine bathers contacting indicator microorganisms of sewage pollution. Marine pollution bulletin. 2003; 46(6):791-4.	E	This study did not measure a direct health outcome. In this study, a participant was fitted with a face mask that contained cloth filters, and then they carried out activity (bathing, swimming and body boarding). The concentrations of pathogens found on the filter were enumerated to estimate potential exposure.
Brinks MV, Dwight RH, Osgood ND, Sharavanakumar G, Turbow DJ, El-Gohary M, et al. Health risk of bathing in Southern California coastal waters. Archives of environmental & occupational health. 2008; 63(3):123-35.	E	This is a modelling study which does not directly measure exposure and health outcomes. Estimates of excess GI risk were based on Cabelli *et al.* 1982 and Kay *et al.* 1994.
Colford JM, Jr., Schiff KC, Griffith JF, Yau V, Arnold BF, Wright CC, et al. Using rapid indicators for Enterococcus to assess the risk of illness after exposure to urban runoff contaminated marine water. Water research. 2012 ; 46(7):2176-86.	I	Included
Colford JM, Jr., Wade TJ, Schiff KC, Wright CC, Griffith JF, Sandhu SK, et al. Water quality indicators and the risk of illness at beaches with nonpoint sources of fecal contamination. Epidemiology (Cambridge, Mass). 2007 Jan;18(1):27-35.	I	Included
Cordero L, Norat J, Mattei H, Nazario C. Seasonal variations in the risk of gastrointestinal illness on a tropical recreational beach. Journal of water and health. 2012 Dec;10(4):579-93.	I	Included
Coudert C, Beau F, Berlioz-Arthaud A, Melix G, Devaud F, Boyeau E, et al. Human leptospirosis in French polynesia. Epidemiological, clinical and bacteriological features. Medecine Tropicale. 2007;67(2):137-44.	E	This study evaluated leptospirosis in French Polynesia.
Diallo MB, Anceno AJ, Tawatsupa B, Houpt ER, Wangsuphachart V, Shipin OV. Infection risk assessment of diarrhea-related pathogens in a tropical canal network. The Science of the total environment. 2008 Dec 15;407(1):223-32.	E	This study was conducted in urban canals in Thailand and was not considered to be relevant to Europe.
Dickinson G, Lim KY, Jiang SC. Quantitative microbial risk assessment of pathogenic vibrios in marine recreational waters of southern california. Applied and environmental microbiology. 2013 Jan;79(1):294-302.	E	This is a modelling study which does not directly measure health outcomes. This study only measures three types of vibrios (bacteria).
Donovan EP, Staskal DF, Unice KM, Roberts JD, Haws LC, Finley BL, et al. Risk of gastrointestinal disease associated with exposure to pathogens in the sediments of the Lower Passaic River. Applied and environmental microbiology. 2008 Feb;74(4):1004-18.	E	This is a modelling study which does not directly measure exposure and health outcomes.
Dorevitch S, Dworkin MS, DeFlorio SA, Janda WM,	I	Included

Reference		Reason for exclusion
Wuellner J, Hershow RC. Enteric pathogens in stool samples of Chicago-area water recreators with new-onset gastrointestinal symptoms. Water research. 2012;46(16):4961-72.		
Dorevitch S, Pratap P, Wroblewski M, Hryhorczuk DO, Li H, Liu LC, et al. Health risks of limited-contact water recreation. Environmental health perspectives. 2012 Feb;120(2):192-7.	I	Included
Dwight RH, Baker DB, Semenza JC, Olson BH. Health effects associated with recreational coastal water use: urban versus rural California. American journal of public health. 2004 Apr;94(4):565-7.	I	Included
Esiobu N, Green M, Echeverry A, Bonilla TD, Stinson CM, Hartz A, et al. High numbers of Staphylococcus aureus at three bathing beaches in South Florida. International journal of environmental health research. 2013;23(1):46-57.	I	This study did not evaluate FIOs of interest: the main aim was to compare contamination (with *S. aureus*) of dry sand and seawater at three beaches during one year.
Eze JI, Scott EM, Pollock KG, Stidson R, Miller CA, Lee D. The association of weather and bathing water quality on the incidence of gastrointestinal illness in the west of Scotland. Epidemiology and infection. 2013 Sep 6:1-11.	E	This is a modelling study which does not directly measure exposure and health outcomes. Cases of viral and non-viral GI pathogens were supplied by Health Protection Scotland.
Fleisher JM, Fleming LE, Solo-Gabriele HM, Kish JK, Sinigalliano CD, Plano L, et al. The BEACHES Study: health effects and exposures from non-point source microbial contaminants in subtropical recreational marine waters. International journal of epidemiology. 2010 Oct;39(5):1291-8.	I	Included
Fleisher JM, Kay D. Risk perception bias, self-reporting of illness, and the validity of reported results in an epidemiologic study of recreational water associated illnesses. Marine Pollution Bulletin. 2006 Mar;52(3):264-8.	E	This study uses data from four previously reported RCTs to evaluate the magnitude and effect of possible 'risk perception bias'.
Fleming LE, Solo GH, Elmir S, Shibata T, Squicciarini D, Jr., Quirino W, et al. A Pilot Study of Microbial Contamination of Subtropical Recreational Waters. Florida journal of environmental health. 2004 Jan 1;184:29.	I	Included
Given S, Pendleton LH, Boehm AB. Regional public health cost estimates of contaminated coastal waters: a case study of gastroenteritis at southern California beaches. Environmental science & technology. 2006 Aug 15;40(16):4851-8.	E	This study estimates the health costs associated with coastal water contamination. Health outcomes are reported as predictions based on modelling.

Reference		Reason for exclusion
Hamner S, Tripathi A, Mishra RK, Bouskill N, Broadaway SC, Pyle BH, et al. The role of water use patterns and sewage pollution in incidence of water-borne/enteric diseases along the Ganges river in Varanasi, India. International journal of environmental health research. 2006 Apr;16(2):113-32.	E	This study was conducted in India and was not considered to be relevant to Europe.
Harder-Lauridsen NM, Kuhn KG, Erichsen AC, Molbak K, Ethelberg S. Gastrointestinal Illness among Triathletes Swimming in Non-Polluted versus Polluted Seawater Affected by Heavy Rainfall, Denmark, 2010-2011.	I	Included
Heaney CD, Sams E, Dufour AP, Brenner KP, Haugland RA, Chern E, et al. Fecal indicators in sand, sand contact, and risk of enteric illness among beachgoers. Epidemiology (Cambridge, Mass). 2012 Jan;23(1):95-106.	E	This study evaluated contact with beach sand risk of illness (i.e. water contact and risk of illness was not evaluated).
Heaney CD, Sams E, Wing S, Marshall S, Brenner K, Dufour AP, et al. Contact With Beach Sand Among Beachgoers and Risk of Illness. American Journal of Epidemiology. 2009 Jul;170(2):164-72.	E	This study evaluated faecal indicators, contact with beach sand and risk of illness (i.e. water contact and risk of illness was not evaluated).
Hussein KR, Bradley G, Glegg G. An evaluation of bacterial source tracking of faecal bathing water pollution in the Kingsbridge estuary, UK. Kay D, Fricker C, editors. Cambridge: Royal Soc Chemistry; 2012. 114-22 p.	E	This study evaluated MST at recreational beaches (not within the scope of this review).
Iwamoto M, Hlady G, Jeter M, Burnett C, Drenzek C, Lance S, et al. Shigellosis among swimmers in a freshwater lake. Southern medical journal. 2005 Aug;98(8):774-8. .	E	Epidemiological study (retrospective cohort) investigating how many people were infected with Shigella after spending time in a lake over a particular weekend. Not relevant to Europe.
Koay TK, Nirmal S, Noitie L, Tan E. An epidemiological investigation of an outbreak of leptospirosis associated with swimming, Beaufort, Sabah. The Medical journal of Malaysia. 2004 Oct;59(4):455-9.	E	This study evaluated leptospirosis in Kuala Lumpur; not a relevant indicator organism and not considered to be relevant to Europe.
Kundu A, McBride G, Wuertz S. Adenovirus-associated health risks for recreational activities in a multi-use coastal watershed based on site-specific quantitative microbial risk assessment. Water research. 2013 Oct 15;47(16):6309-25.	E	This study evaluated adenovirus illness. It is also a modelling study and does not directly measure exposure and health outcomes.
Lepesteur M, McComb AJ, Moore SA. Do we all face the same risk when bathing in the estuary? Water research. 2006 Aug;40(14):2787-95.	E	This study presented results for respiratory illness only. An attempt was made to contact authors for full details of the results, but the authors did not respond.

Reference		Reason for exclusion
Lin CJ, Heaney CD, Wade TJ, Noble RT, Wing S. A repeated-measures study of recreational water exposure, non-point source pollution, and risk of illness. American Journal of Epidemiology. 2013;177:S156.	E	Results only presented for 'any illness'.
Linn KJ. High sensitivity of children to swimming-associated gastrointestinal illness. Epidemiology (Cambridge, Mass). 2009;20(1):156-7.	E	Letter to the editor regarding the study by Wade *et al*. 2008.
Loge FJ, Lambertini E, Borchardt MA, Basagaoglu H, Ginn TR. Effects of etiological agent and bather shedding of pathogens on interpretation of epidemiological data used to establish recreational water quality standards. Risk analysis: an official publication of the Society for Risk Analysis. 2009 Feb;29(2):257-66.	E	This is a methodology/modelling paper.
Marion JW, Lee J, Lemeshow S, Buckley TJ. Association of gastrointestinal illness and recreational water exposure at an inland U.S. beach. Water research. 2010 Sep;44(16):4796-804.	I	Included
McBride GB, Stott R, Miller W, Bambic D, Wuertz S. Discharge-based QMRA for estimation of public health risks from exposure to stormwater-borne pathogens in recreational waters in the United States. Water research. 2013 Sep 15;47(14):5282-97.	E	This study does not measure a health outcome. The study uses QMRA to estimate public health risks from recreational exposure, at sites downstream of multiple discharges.
Papastergiou P, Mouchtouri V, Pinaka O, Katsiaflaka A, Rachiotis G, Hadjichristodoulou C. Elevated bathing-associated disease risks despite certified water quality: a cohort study. International journal of environmental research and public health. 2012 May;9(5):1548-65.	I	Included
Papastergiou P, Mouchtouri VA, Rachiotis G, Pinaka O, Katsiaflaka A, Hadjichristodoulou C. Bather density as a predominant factor for health effects related to recreational bathing: results from the Greek bathers cohort study. Marine pollution bulletin. 2011 Mar;62(3):590-5.	I	Included
Peluso FGC, José. Evaluación del riesgo para la salud del baño recreativo en cursos de agua en la provincia de Buenos Aires, Argentina / Risk assessment of recreational bathing in water courses in the Province of Buenos Aires, Argentina. Salud(i)cienc, (Impresa);. 2012;19(2). Spanish.	E	Full paper could not be retrieved, but may not be relevant to the Europe.
Promoting the healthy, safe use of recreational waters. 2003. Revista panamericana de salud publica. Pan American journal of public health. 2003 Nov;14(5):364-9.	E	Review; no data reported.
Ravel A, Nesbitt A, Pintar K, Macarthur A, Wang HL, Marshall B, et al. Epidemiological and clinical description of the top three reportable parasitic diseases in a Canadian community. Epidemiology and infection. 2013 Feb;141(2):431-42.	E	This study investigated all reported cases of amoebiasis, cryptosporidiosis and giardiasis in one Canadian community.

Reference		Reason for exclusion
Roberts JD, Silbergeld EK, Graczyk T. A Probabilistic risk assessment of cryptosporidium exposure among Baltimore urban anglers. Journal of Toxicology and Environmental Health-Part a-Current Issues. 2007;70(18):1568-76.	E	No direct health outcome data reported; fish and hand wash samples were collected; risk of infection was modelled.
Rose MA, Dhar AK, Brooks HA, Zecchini F, Gersberg RM. Quantitation of hepatitis A virus and enterovirus levels in the lagoon canals and Lido beach of Venice, Italy, using real-time RT-PCR. Water research. 2006 Jul;40(12):2387-96.	E	This study investigated the concentration of viruses in the lagoon water of Venice. Health risk was estimated based on the levels of virus detected, so not measured directly.
Schets FM, van Wijnen JH, Schijven JF, Schoon H, de Roda Husman AM. Monitoring of waterborne pathogens in surface waters in amsterdam, the Netherlands, and the potential health risk associated with exposure to cryptosporidium and giardia in these waters. Applied and environmental microbiology. 2008 Apr;74(7):2069-78.	E	This study estimates risk of infection; it does not directly measure exposure and health outcomes.
Schijven J, de Roda Husman AM. A survey of diving behaviour and accidental water ingestion among Dutch occupational and sport divers to assess the risk of infection with waterborne pathogenic microorganisms. Environmental health perspectives. 2006 May;114(5):712-7.	E	This study compared risk of infection for occupational vs. sport divers based on the volume of water swallowed. The authors did not report an OR comparing the two types of bathers.
Schoen ME, Ashbolt NJ. Assessing pathogen risk to swimmers at non-sewage impacted recreational beaches. Environmental science & technology. 2010 Apr 1;44(7):2286-91.	E	This study estimates risk of infection using a QMRA approach; it does not directly measure exposure and health outcomes.
Schoen MF, Ashbolt NJ. Assessing Pathogen Risk to Swimmers at Non-Sewage Impacted Recreational Beaches. Environmental science & technology.	E	Same study as Schoen *et al.* 2010.
Schonberg-Norio D, Sarna S, Hanninen ML, Katila ML, Kaukoranta SS, Rautelin H. Strain and host characteristics of Campylobacter jejuni infections in Finland. Clinical Microbiology and Infection. 2006 Aug;12(8):754-60.	E	In this study, swimming is one of a number of sources investigated as potential route of infection. It is a follow up to Schonberg-Norio *et al.* 2004.
Schonberg-Norio D, Takkinen J, Hanninen ML, Katila ML, Kaukoranta SS, Mattila L, et al. Swimming and Campylobacter infections. Emerging infectious diseases. 2004 Aug;10(8):1474-7.	E	This study used multivariate analysis to evaluate risk factors (including swimming in water from natural sources) for domestically acquired campylobacter infection.
Sinigalliano CD, Fleisher JM, Gidley ML, Solo-Gabriele HM, Shibata T, Plano LR, et al. Traditional and molecular analyses for fecal indicator bacteria in non-point source subtropical recreational marine waters. Water research. 2010 Jul;44(13):3763-72.	I	Included

Reference		Reason for exclusion
Standish-Lee P, Loboschefsky E. Protecting public health from the impact of body-contact recreation. Water science and technology : a journal of the International Association on Water Pollution Research. 2006;53(10):201-7.	E	Review; no data reported.
Stone DL, Harding AK, Hope BK, Slaughter-Mason S. Exposure assessment and risk of gastrointestinal illness among surfers. Journal of toxicology and environmental health Part A. 2008;71(24):1603-15.	E	This is a modelling study which does not directly measure exposure and health outcomes.
Sunger N, Teske SS, Nappier S, Haas CN. Recreational use assessment of water-based activities, using time-lapse construction cameras. Journal of exposure science & environmental epidemiology. 2012 May-Jun;22(3):281-90.	E	This study reported patterns of water use (using time-lapse construction cameras) and how it varied by weather and day of week. No health outcome data was reported.
Tseng LY, Jiang SC. Comparison of recreational health risks associated with surfing and swimming in dry weather and post-storm conditions at Southern California beaches using quantitative microbial risk assessment (QMRA). Marine pollution bulletin. 2012 May;64(5):912-8.	E	This is a modelling study which does not directly measure exposure and health outcomes.
Tserendorj A, Anceno AJ, Houpt ER, Icenhour CR, Sethabutr O, Mason CS, et al. Molecular techniques in ecohealth research toolkit: facilitating estimation of aggregate gastroenteritis burden in an irrigated periurban landscape. EcoHealth. 2011 Sep;8(3):349-64.	E	This is a modelling study which does not directly measure exposure and health outcomes. This study was conducted in Thailand and may not be relevant to Europe.
Tugrul-Icemer G, Topaloglu A. Levels of Yeast Mold and Pseudomonas spp. in Antalya Beaches. Journal of Coastal Research. 2011:452-7.	E	This study sampled for yeast, moulds and *Psuedomonas spp*. in sand and water, but did not collect data on health outcomes. This study was conducted in Turkey and may not be relevant to Europe.
Turbow DJ, Osgood ND, Jiang SC. Evaluation of recreational health risk in coastal waters based on enterococcus densities and bathing patterns. Environmental health perspectives. 2003 Apr;111(4):598-603.	E	This is a modelling study which does not directly measure exposure and health outcomes.
Viau EJ, Lee D, Boehm AB. Swimmer risk of gastrointestinal illness from exposure to tropical coastal waters impacted by terrestrial dry-weather runoff. Environmental science & technology. 2011 Sep 1;45(17):7158-65.	E	This is a modelling study which does not directly measure exposure and health outcomes. This study was conducted in Hawai'i and may not be relevant to Europe.
Wade TJ, Calderon RL, Brenner KP, Sams E, Beach M, Haugland R, et al. High sensitivity of children to swimming-associated gastrointestinal illness: results using a rapid assay of recreational water quality. Epidemiology (Cambridge, Mass). 2008 May;19(3):375-83.	I	Included

Reference		Reason for exclusion
Wade TJ, Calderon RL, Sams E, Beach M, Brenner KP, Williams AH, et al. Rapidly measured indicators of recreational water quality are predictive of swimming-associated gastrointestinal illness. Environmental health perspectives. 2006 Jan;114(1):24-8.	I	Included
Wade TJ, Converse RR, Sams EA, Williams AH, Hudgens E, Dufour AP. Gastrointestinal symptoms among swimmers following rain events at a beach impacted by urban runoff. American Journal of Epidemiology. 2013;177:S157.	I	Included
Wade TJ, Sams E, Brenner KP, Haugland R, Chern E, Beach M, et al. Rapidly measured indicators of recreational water quality and swimming-associated illness at marine beaches: a prospective cohort study. Environmental health: a global access science source. 2010;9:66.	I	Included
Wade TJ, Sams E, Brenner KP, Haugland R, Wymer L, Dufour AP. High sensitivity of children to swimming-associated gastrointestinal illness. Epidemiology (Cambridge, Mass). 2009;20(1):157.	E	Response to a comment by Linn *et al.* 2009.
Wei A, Dongqing Z, Shumin X, Jianwei Y, Min Y. Quantitative Health Risk Assessment of Cryptosporidium in Rivers of Southern China Based on Continuous Monitoring. Environmental science & technology. 2011;45(11):4951-8.	E	This modelling study evaluated cryptosporidium in rivers in southern China; not relevant indicator organism, and also likely not relevant to Europe.
Wiedenmann A, Kruger P, Dietz K, Lopez-Pila JM, Szewzyk R, Botzenhart K. A randomized controlled trial assessing infectious disease risks from bathing in fresh recreational waters in relation to the concentration of Escherichia coli, intestinal enterococci, Clostridium perfringens, and somatic coliphages. Environmental health perspectives. 2006 Feb;114(2):228-36.	I	Included
Wong M, Kumar L, Jenkins TM, Xagoraraki I, Phanikumar MS, Rose JB. Evaluation of public health risks at recreational beaches in Lake Michigan via detection of enteric viruses and a human-specific bacteriological marker. Water research. 2009 Mar;43(4):1137-49.	E	This is a modelling study which does not directly measure exposure and health outcomes.
Zmirou D, Pena L, Ledrans M, Letertre A. Risks associated with the microbiological quality of bodies of fresh and marine water used for recreational purposes: Summary estimates based on published epidemiological studies. Archives of Environmental Health. 2003 Nov;58(11):703-11.	E	Meta-analysis of results of 18 published epidemiological studies (considered in discussion).

Appendix E: Quality Assessment of included studies

Author(s)/ study	Study design	How was exposure status assigned?	Were participants representative of the general population? Were the comparator groups similar at baseline?	Were water samples taken near exposed individuals?	Were participants assigned an individual exposure?	How was exposure assessed?	How was GI assessed?	Length of follow-up (days)	RCT: dropout rates Observational: Loss to follow-up
Marine									
Abdelzaher et al. 2011; Fleisher et al. 2010; Sinigalliano et al. 2010 BEACHES	RCT	Randomised; block size consisted of a random ordering of blocks of 2, 4, and 6 study participants per individual block; the authors did not explicitly state how they randomised the order of the blocks	No significant differences in demographics between groups	Participants collected samples themselves in their designated bathing area	NR	Supervised by investigator	No GI at baseline Self-reported	7	Drop-outs were not reported by group; of 1,341 participants originally included, overall 38 (2.9%) were lost to follow-up and were not included in the analyses. This small percentage is unlikely to alter study results.
Arnold et al. 2013	Observational	Self-selected	Bathers of all age groups/sex/ethnic background were included in the cohort. Swimmers more likely to be younger and male.	Samples collected from five sites along beach	Site-specific daily average	Self-reported	No GI at baseline Self-reported	10	Response rate 72.15%

Author(s)/ study	Study design	How was exposure status assigned?	Were participants representative of the general population? Were the comparator groups similar at baseline?	Were water samples taken near exposed individuals?	Were participants assigned an individual exposure?	How was exposure assessed?	How was GI assessed?	Length of follow-up (days)	RCT: dropout rates Observational: Loss to follow-up
Bonilla et al. 2007	Observational	Self-selected	Any beachgoer eligible for inclusion. Comparators drawn from the general population.	NR	No	Self-reported	Self-reported	NR	NR
Colford et al. 2007 NEEAR	Observational	Self-selected	Bathers of all age groups/sex/ethnic background were included in the cohort, which likely reflects regular bathers in community. Non-swimmers were likely to be older.	NR	Only one sample taken a day for culture enterococci	Self-reported	Self-reported	14	Response rate 70.55%
Colford et al. 2012	Observational	Self-selected	Likely to reflect bathing community, as all beachgoers were eligible for inclusion. Non-bathers more likely to be female.	Collected from five points placed near participants	Site-specific mean daily average reported	Self-reported	Self-reported	10–14	NR; authors state they hoped for 12,230 participants and they included 9,525
Cordero et al. 2012	Observational	Self-selected	Likely to reflect the community, as anyone visiting beach was eligible for inclusion. Children only excluded if not accompanied by an adult. Non-bathers likely to be older.	Samples collected from points along three transects which enclosed the swimming zone.	Mean daily average reported.	Self-reported	Self-reported	10–12	Response rate bathers 91.52%; non-bathers 87.42%

Author(s)/ study	Study design	How was exposure status assigned?	Were participants representative of the general population? Were the comparator groups similar at baseline?	Were water samples taken near exposed individuals?	Were participants assigned an individual exposure?	How was exposure assessed?	How was GI assessed?	Length of follow-up (days)	RCT: dropout rates Observational: Loss to follow-up
Dwight et al. 2004	Observational	Self-selected	Surfers No comparator group	Water samples not taken by investigators. Based on public health agency data.	No	Self-reported	Self-reported	3 months retrospectively	Sample size was generally very small, with only 241 people in the initial interview and 208 in the follow-up. It is not clear which groups the participants who were lost were in, and the publication states only that some were lost to ineligibility.
Fleming et al. 2004	Observational	Self-selected	The age range of participants was 1–76 yrs. The ratio of men to women was 50:50. No comparator group.	nr	NR	Self-reported	Self-reported	8–10	Response rate 86.34%
Harder-Lauridsen et al. 2013	Observational	Self-selected	Competitors in a triathlon No comparator group	Water quality estimates based on modelling	No	Self-reported	Self-reported	Questionnaires administered up to 1 month after event	Response rate 57% (in 2010) and 54% (in 2011)
Papastergiou et al. 2011 Greek Bathers Cohort	Observational	Self-selected	Local residents. Comparators were non-swimmers attending the beach, who were more likely to be older and in worse health.	Samples taken once per day at a total of seven sampling points located along the line with highest bathing density.	No – daily average	Self-reported	Self-reported	10	Response rate 92.45%

Author(s)/ study	Study design	How was exposure status assigned?	Were participants representative of the general population? Were the comparator groups similar at baseline?	Were water samples taken near exposed individuals?	Were participants assigned an individual exposure?	How was exposure assessed?	How was GI assessed?	Length of follow-up (days)	RCT: dropout rates Observational: Loss to follow-up
Wade et al. 2010 NEEAR	Observational	Self-selected	75% of children aged 5–10 immersed their body, compared with only 26% of those over 65. Swimming was also associated with male gender, non-white race, less frequent visits to the beach, the absence of chronic illnesses or less frequent consumption of raw or undercooked meat Bathers of all age groups/sex/ethnic background were included in the cohort. Study was conducted during the weekend and holidays; therefore it not clear if this is the 'normal' bathing community.	Collected from points along three transects which enclosed the swimming zone.	No – results provided by time of day (8:00 a.m., 11:00 a.m., 15:00 p.m.) and overall daily average.	Self-reported	No GI at baseline. Self-reported	10–12	A total of 9,069 beachgoers were offered enrolment. Of these, 1,715 (19%) refused to participate or were ineligible. Of those who agreed to participate, 6,350 (78%) completed the telephone interview and were eligible for inclusion in the analysis.
Wade et al. 2013	Observational	Self-selected	NR	NR	NR	Self-reported	Self-reported	10–12	NR

Author(s)/ study	Study design	How was exposure status assigned?	Were participants representative of the general population? Were the comparator groups similar at baseline?	Were water samples taken near exposed individuals?	Were participants assigned an individual exposure?	How was exposure assessed?	How was GI assessed?	Length of follow-up (days)	RCT: dropout rates Observational: Loss to follow-up
Fresh water									
Dorevitch et al. 2012a & 2012b	Observational	Self-selected	People engaged in recreational activities. Likely to reflect the water user community, as anyone visiting study locations could participate, including children under 18 if consent given by an adult. Exposed and unexposed groups reported to be demographically similar.	No – water quality only available for one out of the three study periods. Sampling method NR	No	Self-reported	No GI at baseline Self-reported	2, 5 and 21	Response rate 96.3%
Marion et al. 2010	Observational	Self-selected	Swimmers likely to be younger than non-swimmers.	One sample taken per day from centre of beach	No – one sample taken per day	Self-reported	Self-reported	8–9	44% retention rate

Author(s)/ study	Study design	How was exposure status assigned?	Were participants representative of the general population? Were the comparator groups similar at baseline?	Were water samples taken near exposed individuals?	Were participants assigned an individual exposure?	How was exposure assessed?	How was GI assessed?	Length of follow-up (days)	RCT: dropout rates Observational: Loss to follow-up
Wade et al. 2006 & 2008 NEEAR	Observational	Self-selected	Swimmers were younger and more likely to male than non-swimmers. Study conducted during the weekend and holidays; it is therefore not clear if this is the 'normal' bathing community.	Collected from points along three transects which enclosed the swimming zone.	No – average results provided for three points of time (08:00 a.m., 11:00 a.m., 15:00 p.m.) and overall daily average	Self-reported	No GI at baseline Self-reported	10–12	NR
Wiedenmann et al. 2006	RCT	Randomly assigned to bather or non-bather group using a block-randomisation procedure. Children were allowed to choose whether to be randomised with a parent or on their own.	Not clear (only age and sex data reported, which were similar between groups)	Samples were collected from the centre of the designated swimming/non-swimming zones every 20 min	Yes – the microbial concentration individually assigned to each of the bathers, calculated by arithmetic interpolation. Individuals for whom one or more specific concentrations were not available (they entered water too early/late) were excluded from further analysis.	By investigator; recorded length of time spent in water and number of times head immersed	No GI at baseline 1 week after trial, participants were interviewed and inspection made by doctor of throat, eyes and ears. After 3 weeks participants answered a written questionnaire to self-report symptoms.	after 7 and 21	No imbalance in dropout rates between groups