Microbiological assessment of private drinking water supplies in Co. Cork, Ireland

Fabio Bacci and Deborah V. Chapman

ABSTRACT

The microbiological quality of 75 private drinking water supply boreholes in Co. Cork, Ireland was assessed in order to determine the incidence of contamination and the potential pathways of such contamination. Microbiological analysis was carried out using the membrane filtration technique for the recovery of thermotolerant (faecal) coliforms. The sanitary protection of the supplies was evaluated by means of systematic inspections and subsequent qualitative sanitary risk assessment. Almost a quarter of all supplies investigated (24%, $n = 18$) was found positive for thermotolerant coliforms. Weather conditions had a significant impact on microbiological water quality, increasing both contamination incidence and gross contamination frequency. Over half of the supplies had nine or more sanitary hazards and most had rudimentary sanitary protection measures at the head of the borehole. These low sanitary protection measures suggest that boreholes can pose a significant hazard to valuable groundwater resources by providing direct contamination routes.

Key words | domestic supplies, drinking water boreholes, faecal coliforms, groundwater quality, sanitary risk assessment, thermotolerant coliforms

Fabio Bacci (corresponding author)
10 The Green,
Bracken Court,
Donnybrook,
Douglas, Cork,
Ireland
E-mail: *f.bacci@live.ie*

Deborah V. Chapman
School of Biological,
Earth and Environmental Sciences,
University College Cork,
Enterprise Centre, North Mall Campus,
Cork,
Ireland

INTRODUCTION

Absence of thermotolerant (faecal) coliforms is a prerequisite for water sources to qualify as safe drinking water supplies (EU 1998; Irish Statute 2007; WHO 2008). Human exposure to faecal contamination can have a wide spectrum of possible health implications, essentially controlled by the infectivity of the zoonotic agent shed by infected hosts (Cliver & Fayer 2004) and the susceptibility of the receptor (Carr 2001). Occurrence of thermotolerant coliforms in Irish groundwater has been officially reported to occur in 34% of routine monitoring samples (EPA 2009; GSI 2009). Detection of faecal pollution in Irish groundwater resources is reportedly declining in recent times; during the 1995 to 2006 period an improvement of ~20% in the occurrence of 'no detection' was observed by the Irish Environmental Protection Agency (EPA) (EPA 2008a, b). Despite the historical improvement, the Agency recently reported that 52% of all monitoring locations showed positive results at least once during the period 2003–2005 (EPA 2006), a statistic which increased to 58.5% for the period 2004–2006 (EPA 2008a, b), denoting a recent deterioration in microbiological quality. The latest reports suggest further degradation of Irish groundwater, with 67% of monitoring locations showing faecal contamination in at least one sample (EPA 2009). In the past, localised investigations have also found high incidences of contamination, with 47% of groundwater supplies showing microbiological contamination in Co. Wexford, Ireland (GSI 1990) and 45% in the Nore River Basin, Ireland (GSI 1992). Private drinking water supplies in England show similar microbiological quality. Reid *et al.* (2003) determined the occurrence of thermotolerant coliforms in private drinking water supplies in Aberdeenshire, Scotland and found that 25% of samples failed to comply with drinking water standards between August 1997 and July 1998. Rutter *et al.* (2000) recorded *Escherichia coli* (*E. coli*) in 17.0% of boreholes in the UK whereas Fewtrell *et al.* (1998) had reported higher levels of microbiological contamination in borehole supplies in the UK, with an incidence of 36% non-compliance to national standards

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for thermotolerant coliforms, total coliforms or faecal streptococci. Schets *et al.* (2005) however detected a significantly lower thermotolerant coliform incidence of 10.9% in private supplies abstracting groundwater in the Netherlands.

Agricultural practices are often identified as major sources of faecal pollution (Trevisan *et al.* 2002; Taylor *et al.* 2004; Pachepsky *et al.* 2006; Thiagarajan *et al.* 2007; Goss & Richards 2008; Mosaddeghi *et al.* 2009). Animal waste is capable of dispersing pathogens such as bacteria, viruses, protozoa and helminths if not properly contained, treated and managed (Gannon *et al.* 2004). The Walkerton outbreak in Ontario, Canada is a clear example of the risk posed by animal waste and other factors such as abandoned wells (Pedley *et al.* 2006). In this incident pathogenicity attributed to *Campylobacter jejuni* and *E. coli* O157:H7 affected an estimated 2,300 people, seriously debilitating 65 consumers; 27 people developed haemolytic uraemic syndrome (HUS) and seven died (Hrudey *et al.* 2003; WHO 2008). Proprietary on-site treatment and disposal systems are also recognized sources of contamination (Taylor *et al.* 2004; Harden *et al.* 2008). Howard *et al.* (2006) illustrate the risk on-site treatment and disposal systems pose to groundwater quality by drawing on the Washington County Fair case study where a specific septic system was identified as the source of a severe outbreak of *E. coli* O157:H7. Of a total of 781 people affected by either *C. jejuni* or *E. coli*, 71 were hospitalised and 14 developed HUS resulting in two deaths.

Thermotolerant coliforms, enteric organisms excreted by humans and warm-blooded animals, are often referred to as presumptive *E. coli* (Grabow 1996) and can offer an acceptable surrogate indicator for the presence of *E. coli* (WHO 2008). Although faecal indicator bacteria, of which thermotolerant coliforms is a good example, are only indicative of faecal pollution and are not pathogen specific, they still offer a rapid and inexpensive alternative to more sophisticated assays and expensive microarrays (Field & Samadpour 2007). However, presence of these organisms is not indicative of the origin of contamination, whether human or animal, and supplementary bacterial source tracking techniques must be employed when evidence of the source of contamination is necessary (Tallon *et al.* 2005). Sanitary inspections are established methods for the evaluation of sources of contamination and of potential breaches or deficiencies of the sanitary protection system of a supply (WHO 2011). The simplicity of sanitary inspections, and more importantly the resulting systematic reporting, allows for rapid qualitative sanitary risk assessment (Reid *et al.* 2001). Furthermore, consolidation of sanitary risk assessment results with microbiological analysis results can effectively determine the necessary priority of action needed to improve the safety of supplies (Chilton 1996; WHO 2008, 2011).

Current regulations governing the management of private water supplies in Ireland (Irish Statute 2007) assign statutory responsibility to private water providers for periodic quality inspections. Furthermore, the regulations also assign supervisory roles to local authorities and overarching executive obligations to the EPA for the assurance of compliance and delivery of safe water to the consumer (EPA 2010). However, only private supplies providing water to 50 or more persons, or supplying water services to commercial or public activities catering for fewer than 50 persons, are obliged to monitor the water quality regularly. Consequently, small supplies providing water to a few or to single households are exempt from statutory regulations and the responsibility for checking the quality of water supplied is at the discretion of the owner of the supply.

The focal point of this study was to assess private drinking water supplies not governed by the remit of a statutory regulation. The main objectives were to assess the current state of microbiological quality of private drinking water supply boreholes in a delimited area of Co. Cork, Ireland and to conduct a sanitary risk assessment of the monitored supplies with the view to identifying potential causes of contamination and subsequent prioritisation of necessary remedial action.

METHODS

Study area and microbiological sampling regime

The study area covered 1,414 km^2 in Co. Cork, south-west Ireland (Figure 1). A total of 75 boreholes that were in daily use for domestic supply were sampled at least once each between August 2009 and June 2010 according to a protocol based on Bartram *et al.* (1996), WHO (1997), RCPEH (2000) and Myers *et al.* (2007). To guarantee

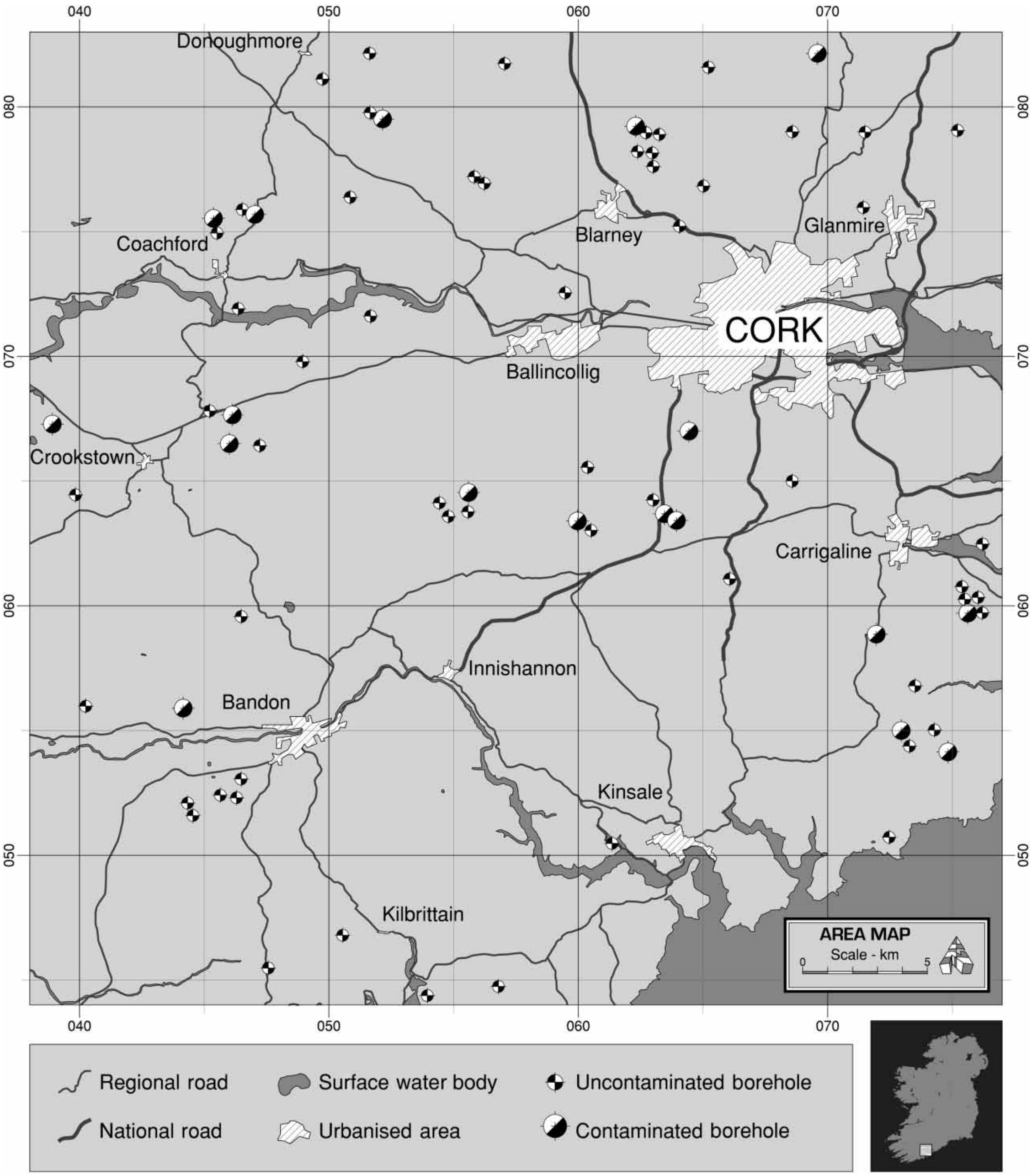

Figure 1 | Location of sampled boreholes in Co. Cork, Ireland indicating supplies that were negative (uncontaminated) and positive for faecal coliforms (contaminated).

homogeneity of data only supplies abstracting groundwater via a borehole structure were surveyed. Participation of owners of private drinking water supplies was obtained by broadcasting an e-mail announcement to all the members of University College Cork staff offering microbiological analysis of drinking water on condition that the household was supplied by groundwater abstracted via a borehole and equipped with an electric submersible pump. Supplies were purged for not less than five minutes at high flow in order to flush the supply network and ensure that the samples were as representative of the microbiological quality of consumed water as possible. Due to restricted access to the sump for measurements of depth of borehole and depth of water for many of the supplies, the purging procedure was standardised at five minutes for all supplies. Aseptic samples were collected in sterile 250 ml polypropylene bottles from kitchen taps or, in cases where disinfection systems were present, at an outlet preceding disinfection. Where, to circumvent disinfection systems, samples were obtained from an external outlet, the tap was disinfected using a naked flame. Samples were preserved in a dark cooler box at ambient temperature for a maximum of 5 hours holding time. On completion of every sampling run, which consisted of a maximum of six samples, a field blank was prepared by transferring distilled water stored in a sterile polypropylene bottle into a second sterile bottle at the site of the last sample and following the same methodology.

The occurrence of recent localised precipitation events were recorded for each sample site according to the supply owner's personal recollection. It was considered more appropriate to rely on individual judgement rather than national statistics due to the significant variability of localised rainfall events (Coffey *et al*. 2010). However, in order to minimise the possibility of introducing bias due to personal judgement, cross checking with the recollection of owners of other supplies also visited in the same area (within ± 2 days), as well as countrywide precipitation reports, was conducted but no adjustments were deemed necessary.

Microbiological analysis was conducted using the membrane filtration technique described by Bartram & Pedley (1996) which was based on the Rapid Test of ISO Standard 9308-1:2000 (ISO 2000) using Membrane Lauryl Sulphate Broth (Product Code MM0615 Oxoid® Ltd, UK) and an incubation temperature of 44 ± 0.5 °C. The choice of method was dictated by a number of factors, namely the versatility of the equipment, the quantitative accuracy of detection of single viable cells (Grabow 1996; Köster *et al*. 2003) and a limited degree of analytical interference, for example by total coliforms (Payment *et al*. 2003). To eliminate the likelihood of contamination during sampling and transit, field blanks were included in each sampling run. Analytical precision was evaluated by duplicate analysis of each sample, following the methodology recommended by Briggs (1996). Spiked samples were periodically used to validate each new batch of lauryl sulphate growth medium and simultaneously validate the analytical effectiveness of the method.

The scale of contamination was categorised by the quantity of colony forming units recovered from each sample (Table 1), based on the approach used by the EPA (EPA 2006, 2008a, b); this situation allowed comparison with existing national data for microbiological quality of groundwater. The nomenclature assigned to each contamination class was however arbitrarily chosen and may not conform to EPA reports.

Sanitary survey and risk ranking

Qualitative sanitary risk assessments of water supplies are intended to identify potential hazards and, by mean of systematic investigative and ranking protocols, evaluate the risk associated with a supply (Reid *et al*. 2001; Giannoulis *et al*. 2005). As recommended by Reid *et al*. (2001) the assessment methodology was intentionally kept simple to facilitate *in-situ* evaluations by means of a sanitary survey and subsequent sanitary risk ranking score, a reportedly valid indicator of microbiological contamination (Howard *et al*. 2003). Diagnosis of potential causes or sources of microbiological contamination was carried out by means of a sanitary survey form that assisted in maintaining a systematic consistency in the methodology of inspection. The structure of the survey was largely adapted from Reid *et al*. (2001), Davison *et al*. (2005) and the Scottish Executive (2006). The survey consisted of two separate inspections, one examining the borehole structure at the surface and one examining the site of the supply. The surveys were carried out by the same person using a series of nine questions per inspection for all 75 surveys in order to prevent bias being introduced by different surveyors. Firstly, inspection of the head of the supply borehole and ancillary sanitary protection measures (Figure 2) was carried out in order to identify non-conformities with recommended, though not mandatory, Irish standards of borehole construction (IGI 2007).

Table 1 | Classification system for contamination of drinking water supplies in Ireland

Microbiological contamination category		Category classification† (CFU 100 ml^{-1})
Uncontaminated		<1
Contaminated	Moderate	1–5
	Serious	6–10
	Severe	11–100
	Acute	>100

†Categories based on the approach used by the EPA (EPA 2006, 2008a, b).

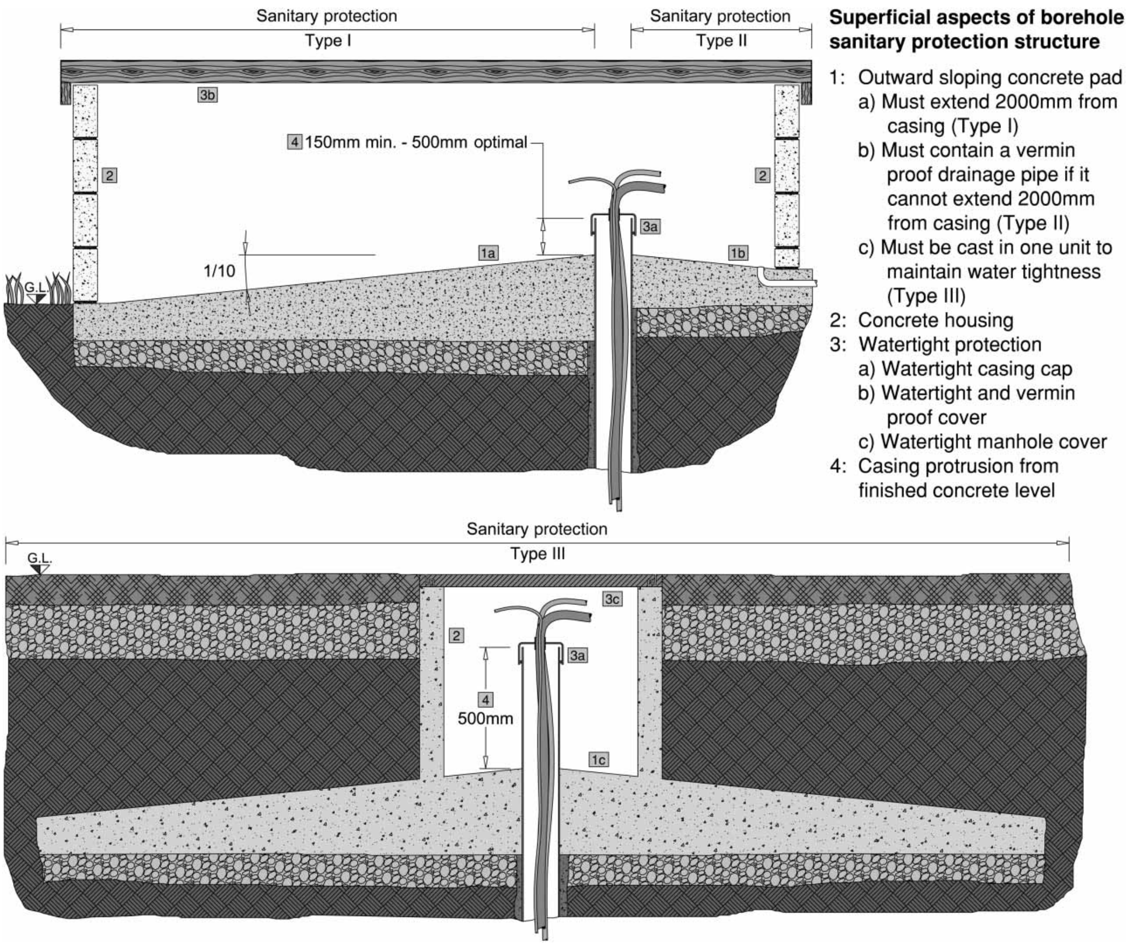

Figure 2 | Desirable borehole sanitary protection measures at the surface according to recommended, though not mandatory, Irish standards of borehole construction (based on IGI 2007).

Further susceptibility of the supply to contamination was assessed by examining the liability of the piping distribution network to fracture as a potential pathway of contamination, the possibility of contamination by animal watering systems connected to the network and the likelihood of intermittent or transient contamination where history of non-compliance existed. Routine disinfection procedures were also recorded. The second inspection examined sanitary hazards within the site. It identified the type of on-site treatment and disposal systems, their proximity to the supply network and the likelihood of poor drainage around the borehole head, potentially leading to entry of contaminated water. Hazardous agricultural activities such as animal waste applications and land uses on adjacent land were recorded, as well as the presence of abandoned wells and boreholes near the site, where knowledge of these features existed. Supplies were allocated two separate scores, one for the borehole and one for the site, according to the number of hazards identified in each section of the survey. The product of the two scores returned the sanitary risk rank of a supply, as illustrated in the risk ranking matrix (Figure 3). The classification obtained from the sanitary risk ranking matrix was generic as it did not give a discriminate estimate of borehole hazards as opposed to site hazards. The advantage, however, was a rapid indication of the risk associated with a supply, in other words the amount of hazards a supply was subject to, for the purpose of a broad risk evaluation of the study area.

A second matrix was used to evaluate the priority of remedial action that would currently be necessary to improve the private drinking water supply boreholes in Co. Cork, Ireland based on the assumption that the

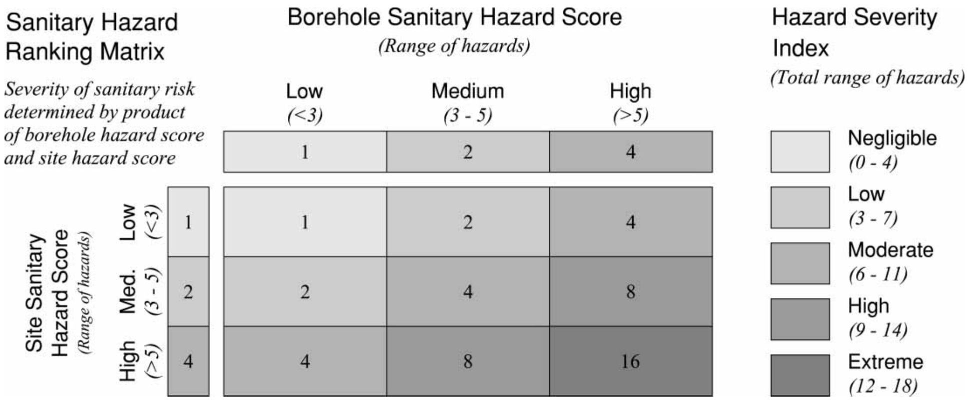

Figure 3 | Sanitary Risk Ranking Matrix for borehole drinking water supplies. The scoring system is produced by the results of two separate site inspections, one examining the borehole structure and one evaluating the microbiological sources and hazards present.

sample within the study area was in fact representative of the region. The score was obtained by combining sanitary risk ranking results with the classification of contamination for all supplies (Figure 4). The structure of the matrix was adapted from established methods (Chilton 1996; Giannoulis *et al.* 2005; WHO 2008) with a simplification of action priority categories. The purpose of the matrix however differed from the aim of the original sources. The goal of the sanitary survey was to establish the overall state of repair of private drinking water supply boreholes, for instance for decision making purposes, in contrast with the objective of Chilton (1996), which was to assess individual supplies in order to allocate available remedial action. The lower limit of the High Priority action in the matrix was intentionally matched with the classification of gross contamination adopted by the Environmental Protection Agency and others (GSI 2000; EPA 2006, 2008a, b) to provide a common benchmark.

RESULTS

The results of the microbiological analysis shown in Table 2 represent the mean of two determinations conducted simultaneously on duplicate 100 ml aliquots of each sample. Nearly one quarter of the supplies sampled (24.0%, $n = 18$) were found to contain thermotolerant coliforms during the sampling campaign. Moderate contamination

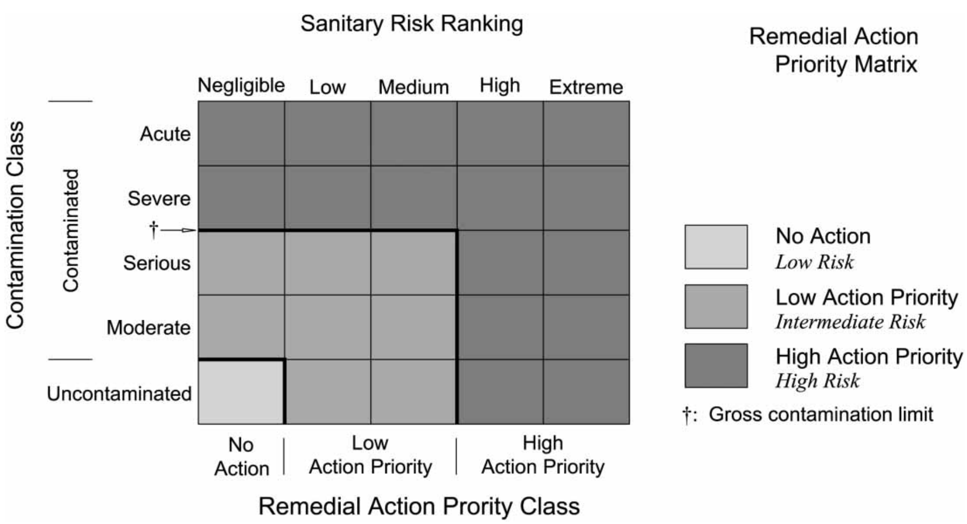

Figure 4 | Remedial Action Priority Matrix for borehole drinking water supplies. The scoring system is produced by the sanitary risk ranking results and the microbiological contamination results, the latter classified according to the number of recovered CFUs (see Table 1).

Table 2 | Summary statistics of thermotolerant coliforms in contaminated borehole supplies in Co. Cork, Ireland denoting contamination categories used and variations in contamination relative to weather pattern

Microbiological contamination category		Category classification (CFU 100 ml^{-1})	No. of boreholes	Proportion of boreholes (%)	Sampled following dry weather† ($n = 61$)	Sampled following wet weather ($n = 14$)
Uncontaminated		<1	57	76.0	49	8
Contaminated	Moderate	1–5	10	13.3	9	1
	Serious	6–10	2	2.7	1	1
	Severe	11–100	4	5.3	1	3
	Acute	>100	2	2.7	1	1
Cumulative contamination		≥1	18	24.0	12	6

†Weather pattern considered for a maximum of three days preceding the sampling.

(1–5 colony forming units (CFU) 100 ml^{-1}) was detected in 13.3% ($n = 10$) of the supplies surveyed. Serious contamination (6–10 CFU 100 ml^{-1}) was detected in two supplies (2.7%) and another four supplies (5.3%) proved to be severely contaminated (11–100 CFU 100 ml^{-1}). Acute contamination (>100 CFU 100 ml^{-1}) was identified in two supplies (2.7%). Weather conditions prior to sampling proved to have a significant impact on the contamination levels. Three of the four severely contaminated supplies were sampled following wet weather. The dry weather and wet weather determinations were found to be significantly different ($U = 307$, $n_{\text{dry}} = 61$, $n_{\text{wet}} = 14$, $P = 0.03$).

The results of the qualitative surveys of the borehole head and ancillary structures together with potential sources of contamination are presented in Table 3, adapted from a format used by Reid *et al.* (2001). The initial four questions (Questions 1.1 to 1.4) of the borehole sanitary inspection assessed the presence and quality of fundamental superficial sanitary protection standards of borehole construction. Results of these questions clearly identified deficiencies and rudimentary sanitary protection measures at surface level (Figure 5).

Historical contamination of the supply (Question 1.8) was ascertained in 17.3% of the boreholes investigated, a factor which reduced the chance of bias being introduced to the study by an increased willingness to participate by concerned supply owners. Inspections of site layouts and land uses determined that household wastewater was handled by on-site treatment and disposal systems in 97.3% of the supplies investigated (Question 2.1), and in 76.0% of these cases the proprietary sewerage ran within a 50 metre radius of the borehole (Question 2.2). Conventional two-chamber septic tanks were the predominant treatment system (86.7%) and only 10.7% of households had a modern self-contained mechanical treatment system (Question 2.9). Although seven out of the eight sites where a modern self-contained mechanical treatment system was installed showed no contamination in the water supply, there was no statistically verifiable difference between contamination and treatment systems. Application of slurry on land adjacent to the supply was confirmed in 57.3% of the supplies (Question 2.3) and livestock in close proximity (<50 m) to the borehole head was confirmed in 49.3% of the supplies (Question 2.5). Presence of abandoned wells or boreholes within a 250 m radius from the supply (Question 2.8) was determined in 21.3% of the sites visited but access to these often derelict structures was limited and sampling was not feasible.

Sanitary hazard score and sanitary risk ranking

While 42.1% of the uncontaminated boreholes investigated showed evidence of more than five hazards, in contaminated boreholes the proportion increased to 72.2% (Figure 6). The sites where uncontaminated supplies were located appeared more protected, with 61.4% showing three to five hazards and only 35.1% with more than five hazards (Figure 6). There was no marked increase in hazards at the sites of contaminated supplies. Four (22.2%) of the contaminated supplies had a known history of contamination and a further four (22.2%) had a connection to an animal watering system. Slurry or manure spreading on land adjacent to the supply was recorded in 44.4% ($n = 8$) of the contaminated cases whereas livestock presence within 50 m of the supply occurred in 66.7%

Table 3 | Summary results of sanitary hazard inspections for boreholes and sites of supplies in Co. Cork, Ireland. The questions shown in the table reflect the questions used in the site inspection form

Survey type		Yes *n*	(%)	No *n*	(%)	NA† *n*	(%)
Borehole Sanitary Hazard Inspection							
1.1	Is there an outward sloping concrete pad surrounding the borehole?	30	*(40.0)*	41	*(54.7)*	4	*(5.3)*
1.2	Is there a concrete housing surrounding the borehole?	30	*(40.0)*	43	*(57.3)*	2	*(2.7)*
1.3	Is the borehole suitably capped with a vermin-proof water tight cover?	20	*(26.7)*	52	*(69.3)*	3	*(4.0)*
1.4	Is the top of casing at least 150 mm above concrete or ground level?	30	*(40.0)*	38	*(50.7)*	7	*(9.3)*
1.5	Is the state of repair of the borehole and ancillary work satisfactory?	24	*(32.0)*	47	*(62.7)*	4	*(5.3)*
1.6	Is the supply network or sewerage made of fracture proof material?	52	*(69.3)*	18	*(24.0)*	5	*(6.7)*
1.7	Is the supply network routinely flushed with a disinfectant?	2	*(2.7)*	72	*(96.0)*	1	*(1.3)*
1.8	Is the supply historically free from microbiological contamination?‡	51	*(68.0)*	13	*(17.3)*	11	*(14.7)*
1.9	Is the supply network free from supplying animal watering systems?	58	*(77.3)*	14	*(18.7)*	3	*(4.0)*
Site Sanitary Hazard Inspection							
2.1	Is there an on site treatment and disposal system (OSTDS)?	73	*(97.3)*	1	*(1.3)*	1	*(1.3)*
2.2	Is the OSTDS or relative sewerage within 50 m of the borehole?	57	*(76.0)*	17	*(22.7)*	1	*(1.3)*
2.3	Is the adjacent land remediated with application of sludge or slurry?	43	*(57.3)*	29	*(38.7)*	3	*(4.0)*
2.4	Is there ever poor drainage with standing water <5 m from the borehole?	11	*(14.7)*	59	*(78.7)*	5	*(6.7)*
2.5	Is livestock ever present <50 m from the borehole?	37	*(49.3)*	35	*(46.7)*	3	*(4.0)*
2.6	Are there either landfill/rubbish tip area or slurry pits in the vicinity?	16	*(21.3)*	56	*(74.7)*	3	*(4.0)*
2.7	Are there springs in the vicinity?	31	*(41.3)*	36	*(48.0)*	8	*(10.7)*
2.8	Are there abandoned wells or boreholes within 250 m of the supply?	16	*(21.3)*	47	*(62.7)*	12	*(16.0)*
2.9	What type of wastewater treatment system is installed on the site? Septic tank (Column I); treatment system (C. II); unknown (C. III)	65	*(86.7)*	8	*(10.7)*	2	*(2.7)*

†NA: information not available.
‡Question 1.8 investigated whether or not supplies had any known history of microbiological contamination.

($n = 12$). The majority of these hazards also appeared to be associated with either breaches of the sanitary protection measures or complete lack of superficial sanitary protection.

The sanitary risk ranking conveyed an overall impression of the degree of sanitary vulnerability between uncontaminated and contaminated supplies (Figure 7). In contaminated supplies there was an apparent increase in frequency of high and extreme classes compared to uncontaminated supplies, and, worthy of note, a small proportion of classes with a low incidence of hazards.

Association between microbiological contamination and sanitary risk

No statistical correlation was found between borehole hazards and thermotolerant coliform loading ($r_s = 0.36$, $n = 18$, $P > 0.05$) and between site hazards and thermotolerant coliform loading ($r_s = 0.25$, $n = 18$, $P > 0.05$). Although not statistically verifiable due to the low number of contaminated samples collected following wet weather conditions ($n = 6$), the likelihood of an association between rainfall and poor sanitary protection may exist; while speculative, this assumption is sustained by four out of the six contaminated samples following wet weather having five or more hazards. The grade of remedial action required to reduce sanitary risk for all supplies was determined by consolidating microbiological contamination and sanitary risk ranking. While the level of remedial action obtained was not supported by statistical evidence of correlation with contamination, the risk analysis still provided a valuable snapshot of the possible prioritization of action required at a regional level. The outcome of this exercise suggested

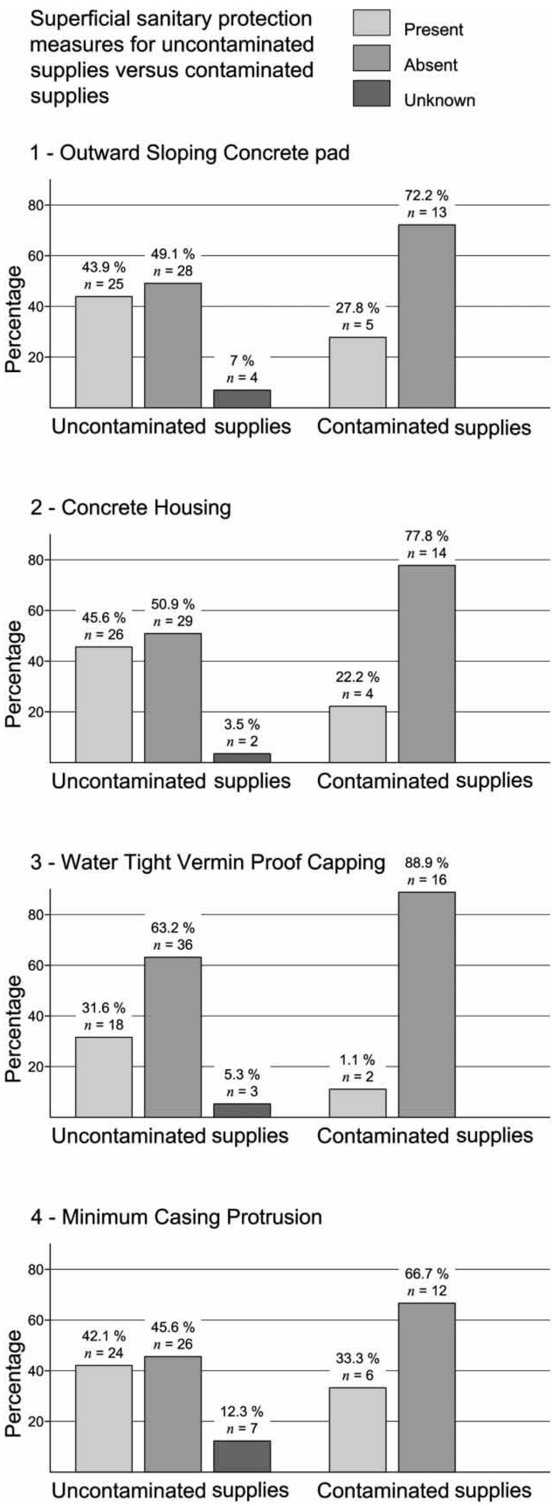

Figure 5 | Summary of four fundamental sanitary protection measures at borehole surface found in the inspections in Co. Cork, Ireland. A persistently higher absence of protection measures in contaminated supplies is apparent when compared with uncontaminated supplies.

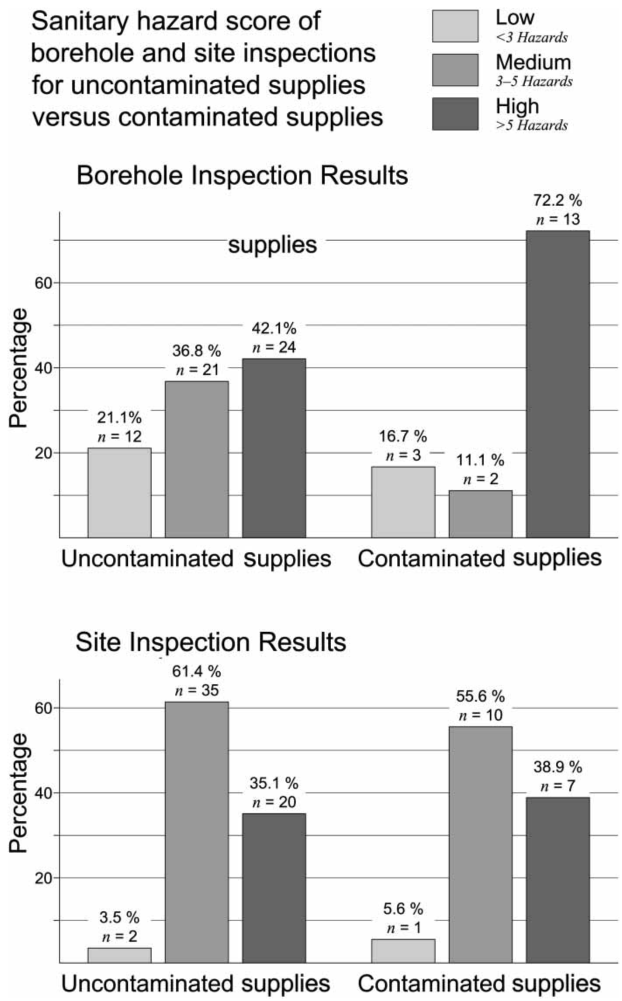

Figure 6 | Summary results of sanitary hazard score of borehole and site inspections for uncontaminated supplies compared with contaminated supplies denoting the significantly higher proportion of hazards identified by borehole inspection of contaminated supplies.

that one supply did not require any remedial action while 32 supplies (42.7%) were categorised as low priority. A total of 42 supplies (56%) were shown to be in need of urgent attention (Figure 8).

DISCUSSION

Results obtained in this study suggest that Co. Cork, Ireland may experience a lower incidence of microbiological contamination in groundwater supplies compared with the latest official reported incidence of 34% of samples in

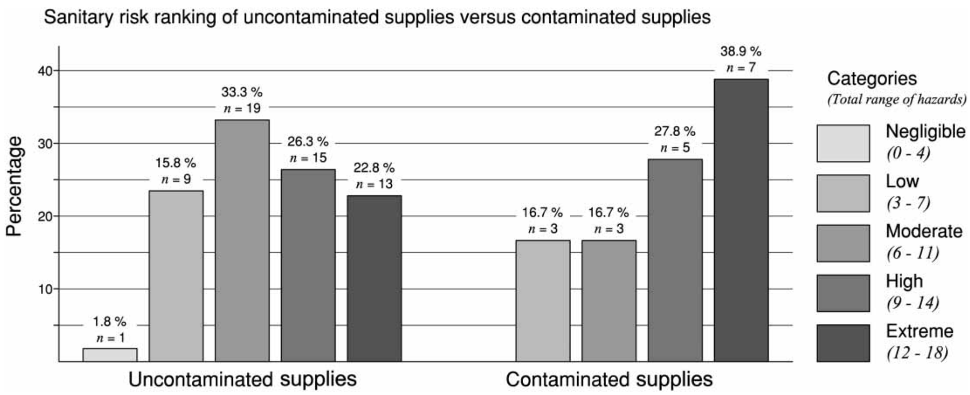

Figure 7 | Summary representation of sanitary risk ranking results for all supplies investigated compared with contaminated supplies (refer to Figure 3 for explanation of ranking), showing the overall higher incidence of hazards for contaminated supplies.

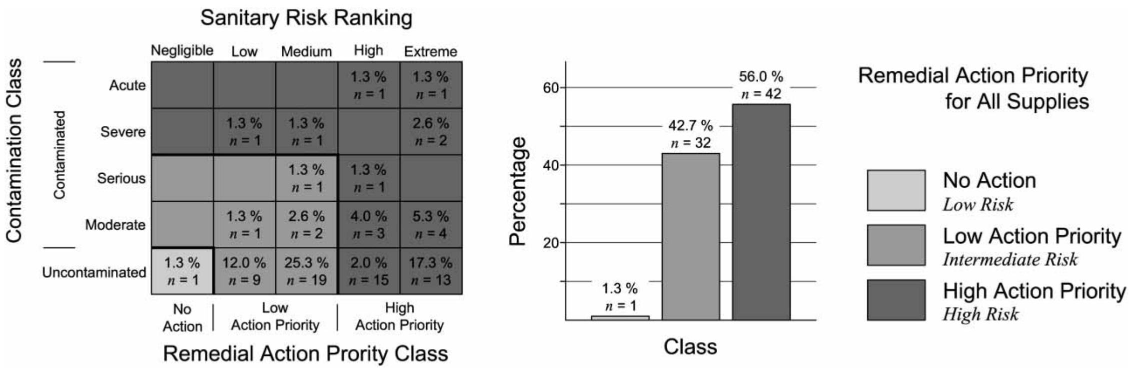

Figure 8 | Summary of proportion of borehole supplies in Co. Cork, Ireland classified as being in need of remedial action based on sanitary risk ranking results and microbiological quality of individual supplies.

Ireland (EPA 2009). From a total of 75 private groundwater supplies tested in this study, 18 (24%) were positive for thermotolerant coliforms at least once and failed to meet the statutory microbiological standards (Irish Statute 2007). Counts of thermotolerant coliforms in excess of 10 per 100 ml are generally regarded as indicating gross contamination in the Irish context (GSI 2000; EPA 2006, 2008a, b). The most recent reports published by the EPA (2009) suggest an incidence of gross contamination in 19% of samples abstracted from locations routinely monitored between 2007 and 2008, whereas this research found that only 8% of samples fell within the severe and acute contamination classes.

The difference between the results of this study (24%) and the reported proportion of positive routine monitoring samples at a national level (34%), and also the variation with the proportion of positive monitoring locations (67%) (EPA 2009), suggests that faecal pollution of groundwater resources in Ireland may be transient in nature. The effect of the preceding weather conditions on the quality of the supplies surveyed in Co. Cork, Ireland indicated that rainfall is a significant factor in contamination frequency. The proportion of supplies showing traces of faecal contamination more than doubled between samples collected following dry weather and samples collected after rainfall. In addition, the increase observed was not merely limited to the proportion of supplies contaminated but more importantly to the intensity of contamination. During dry weather moderate levels of contamination largely dominated the results. In contrast, severe contamination intensified markedly with preceding wet weather conditions. Furthermore, although not verified statistically due to the low number of samples, four out of six contaminated supplies tested after wet weather conditions scored high in the borehole sanitary hazard inspection. This finding suggested that an association between precipitation and poor sanitary protection may exist and govern a transient microbial quality of supplies. The association between microbiological contamination in groundwater and heavy precipitation events has been thoroughly researched and documented (Rutter *et al*. 2000; Olsen *et al*. 2002; Schets *et al*. 2005; Appleyard & Schmoll 2006; Fong *et al*. 2007; Richardson *et al*. 2009). In addition, Curriero *et al*. (2001) conducted extensive research on the relationships between precipitation events and waterborne disease outbreaks over a period spanning almost half a century and concluded that a statistically significant correlation exists. Reports of association between waterborne disease outbreaks and high rainfall periods in Ireland have suggested that private drinking water supplies could be likely sources of the outbreaks (O'Sullivan *et al*. 2008; Garvey *et al*. 2009). O'Sullivan & Brennan (2008) recommended boiling abstracted water during periods of exceptional precipitation, especially where children and elderly people, who are more vulnerable to disease, are present among the users of a groundwater supply.

Qualitative sanitary risk assessment

The objective of the sanitary risk assessment was to generate a systematic qualitative approach for investigating sanitary protection levels and potential pollution sources for borehole supplies. The goal of the exercise had three facets: (i) to categorise supplies under a sanitary risk ranking scale in order to assess the overall sanitary risk of the area surveyed, (ii) to aid in identifying patterns in potential causes of pollution of contaminated supplies, and (iii) to provide a systematic approach for prioritising remedial action. The sanitary risk ranking results (Figure 7) suggested a significant increase in the proportion of hazards associated with contaminated supplies relative to uncontaminated supplies. The borehole sanitary hazard inspections carried out in this study identified the generally poor quality of sanitary protection measures of supplies in Co. Cork, Ireland. Furthermore, absence of superficial sanitary protection measures was more prevalent in the supplies where faecal contamination was detected. Fundamental defences against the ingress of pollutants from the surface or shallow subsurface were, to some degree, absent in all the supplies surveyed and these deficiencies were invariably greater in contaminated supplies. The significant proportion of design flaws or deficiencies of essential protection measures suggested that potential microbiological contamination may in fact ingress the borehole sump from the surface and not necessarily from the groundwater resource. The finding of most concern was the lack of a vermin-proof watertight cover, whether as a steel cap on the borehole casing or as a secure cover on an ancillary concrete housing, in 68.0% of supplies surveyed.

The identification of simple sanitary protection deficiencies raises the concern that, where a source of pollution is present, boreholes can effectively become pathways of contamination for the underlying aquifers (Howard & Schmoll 2006). Case studies, such as the Walkerton outbreak in Ontario, Canada examined by Pedley *et al*. (2006), have suggested that operational and, in particular, abandoned and inadequately sealed boreholes and wells are likely pathways of contamination. The consequences of such pathways vary according to the groundwater flow rate, which is a function of the porosity characteristics of the underlying bedrock (Chilton & Seiler 2006). Additionally, the evidence that contaminated supplies identified in this study suffered a higher rate of deficiency in sanitary protection further substantiates the issue. In contrast with positive results of correlation between thermotolerant coliform loading and risk ranking score obtained by Howard *et al*. (2003), no significant association between contamination and sanitary hazard assessment and risk ranking results were detected in this study. Although the results from the survey have assisted in the identification of hazards and the indexing of risk of supplies as intended, their application in statistical prediction was not possible. The application of non-parametric and nominal scale analyses failed to identify any association between the number of hazards, whether ranked or not, and the contamination levels and classes. Ultimately, the consolidation of microbiological analysis results and sanitary risk ranking was most useful in revealing where remedial action should be directed in order to correct deficiency and prevent excessive and intermediate risk in supplies, and in fact resources, at a regional level, a finding that should attain an application in decision making processes. The function of the sanitary survey, namely to detect system deficiencies and potential sources leading to contamination, remained however as intended and was a valuable instrument in the identification of pathways of contamination and classification of remedial action required for each supply. This study has demonstrated that the application of such an approach can systematically identify areas of concern within a supply protection zone and assist in prioritising essential remedial action.

CONCLUSIONS

Private domestic drinking water supplies in Co. Cork, Ireland were found to suffer from a 24% incidence of microbiological contamination in 2009–2010. There was a significant difference between the number of contaminated and uncontaminated wells sampled during dry weather and wet weather conditions. The study did not attempt to assess the causes of contamination of individual supplies but it did identify a significant increase in breaches of fundamental sanitary protection measures between uncontaminated and contaminated supplies. Sanitary hazards presenting microbiological risk were prominent in most of the supplies inspected. The absence of fundamental sanitary protection measures recommended by standard guidelines suggested that contamination of the wells may not necessarily have been an attribute of the aquifer but possibly due to defects in the sanitary protection measures. Such poorly protected supplies could become hazards to the microbiological quality of local groundwater resources. This conclusion was substantiated by an increased incidence in absence of fundamental sanitary protection measures in supplies found positive for faecal contamination. This finding raises the important question of whether defective supplies could act as potential routes of faecal pollution to valuable groundwater resources.

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