Microbial Contamination of Groundwater at Small Community Water Supplies in Finland

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Abstract The raw water quality and associations between the factors considered as threats to water safety were studied in 20 groundwater supplies in central Finland in 2002–2004. Faecal contaminations indicated by the appearance of *Escherichia coli* or intestinal enterococci were present in five small community water supplies, all these managed by local water cooperatives. Elevated concentrations of nutrients in raw water were linked with the presence of faecal bacteria. The presence of on-site technical hazards to water safety, such as inadequate well construction and maintenance enabling surface water to enter into the well and the insufficient depth of protective soil layers above the groundwater table, showed the vulnerability of the quality of groundwater used for drinking purposes. To minimize the risk of waterborne illnesses, the vulnerable water supplies need to be identified and appropriate prevention measures such as disinfection should be applied.

Keywords Drinking water safety · *E. coli* · Faecal contamination · Groundwater · Small community water supply · Water quality

INTRODUCTION

Small community water supplies are recognized internationally as an issue critical to public health (Anonymous 1997; WHO 1997; Hulsmann 2005). The operation and management of small water supplies may be inadequate due to the limited resources and lack of awareness of factors affecting water quality. The principal public health concern is the use of vulnerable groundwater aquifers without water purification or disinfection measures for drinking purposes. At vulnerable drinking water supplies,

the deficiencies in multi-barrier approach increase the risk of drinking water contamination (Cool et al. 2010; Joerin et al. 2010). The penetration of surface water carrying animal waste or sewage to groundwater abstraction wells may lead to gastrointestinal illnesses (Schijven et al. 2010), as faecal material may contain various pathogenic microbes. The most common causative agents in waterborne gastrointestinal illness outbreaks in developed countries have recently been norovirus, *Campylobacter*, *Cryptosporidium*, *Giardia* and pathogenic *E. coli* (Hrudey and Hrudey 2007). In lesser extent, also rotavirus, *Shigella*, hepatitis A, *Salmonella* and *Toxoplasma* are known to cause waterborne outbreaks.

Many of the waterborne outbreaks have been associated with small water supplies (Hrudey and Hrudey 2004). Accordingly, most of the outbreaks in Finland have occurred in private water systems or in small groundwater supply plants (Miettinen et al. 2001). The groundwater suppliers in Finland often pump the water into their distribution system without treatment or disinfection since groundwater is usually trusted to be of high quality (Lahti and Hiisvirta 1995). The majority of the water suppliers in Finland are small plants, serving at most a few hundred of people. The smallest water supply plants are often managed by local water cooperatives, financed by charging very low operation and maintenance fees, and are often operated by community members working on a voluntary basis, a situation that appears to be the case also in other countries (Hunter et al. 2009). The last official count estimated that there were 1,319 drinking water suppliers serving at least 50 persons in Finland at the end of 1999 (Lapinlampi and Raassina 2002).

The quality of water distributed through community water supplies is regularly monitored. The most commonly used and the best known indicator of faecal contamination

is *Escherichia coli*, indicating recent faecal contamination (Tallon et al. 2005). In microbial water quality monitoring, usually 100 ml volumes of water are tested using culture methods. Microbial indicators more resistant than *E. coli* in environmental conditions, such as intestinal enterococci or *Clostridium perfringens*, or physico-chemical parameters may be used to supplement the quality assessment. According to the European Union Drinking Water Directive (European Union 1998), the sampling frequency for regulatory purposes depends on the volume of water distributed, and at the smallest water supplies (supplies producing 10–50 m³ a day), the required frequency is once per year. Since the events leading to faecal contaminations of water such as rain runoff or melting of snow usually exist for only a few days, it is evident that the once a year monitoring does not truly guarantee the protection of public health.

The aim of the study was to identify the potential hazards compromising the water safety of small and medium scale community water supplies in central Finland. The faecal contamination of water was monitored using enhanced methods including tenfold water volumes and a wide set of indicator and pathogenic microbes, and the characteristics associating with faecal contamination were investigated. This hazard identification should raise awareness of the possible health risks caused by the use of

vulnerable groundwater aquifers for drinking water purposes.

MATERIALS AND METHODS

Study Sites, Sampling and Hazard Identification

We selected 20 water supply plants situated in 19 hydro-geological groundwater formation areas (two water supplies were situated in the same aquifer) in northern Savo, Central Finland, between 62°15' and 63°45'N and 26°30' and 28°30'E. Information on the abundance of the yield of water in the aquifer was the main selection criterion at the study sites, i.e. the water produced by these water supplies was the major water source for local inhabitants, cattle farms or the food processing industry. The selected study sites supplied drinking water for a relatively small number of users, but one important factor was that many of these suppliers did not employ professional personnel to maintain the safety of their drinking water.

The characteristics and the number codes of the studied water supplies are presented in Table 1. The information on land use in the water formation area was obtained from North Savo Regional Environment Centre. Most of the studied groundwater supplies are situated in eskers formed

Table 1 The characteristics of the groundwater supplies studied

Water supply	Number of persons served	Yield of water (m ³ /day)	Principal land use in the water formation area (land use types representing 5% or more are shown)
1 ^a	120	100	Forests (95%)
2	4,500	3,000	Forests (44%) and water bodies (40%)
3 ^a	350	250	Agricultural land (49%) and forests (48%)
4 ^a	140	5,900	Forests (83%) and land reserved for industry (9%)
5 ^a	70	50	Water bodies (72%) and forests (27%)
6 ^a	150	250	Forests (99%)
7 ^a	220	110	Forests (84%) and agricultural land (16%)
8	22,800	17,000	Forests (86%) and agricultural land (7%)
9	450	500	Forests (54%), water bodies (40%) and agricultural land (5%)
10	3,000	950	Forests (71%), agricultural land (7%) and sand and gravel mining (6%)
11 ^a	5,400	900	Forests (81%), agricultural land (12%) and inhabitation (6%)
12	850	600	Forests (53%) and inhabitation (22%)
13	2,450	800	Forests (81%), agricultural land (7%) and sand and gravel mining (5%)
14	3,220	5,700	Forests (87%)
15	2,970	5,300	Forests (87%)
16 ^a	50	300	Forests (66%) and agricultural land (31%)
17	770	1,800	Forests (63%), inhabitation (10%) and agricultural land (7%)
18	2,430	2,200	Forests (61%), water bodies (12%) and agricultural land (9%)
19	430	1,300	Forests (81%) and agricultural land (5%)
20 ^a	90	50	Forests (100%)

^a Water supply managed by local water cooperative (the supplies without a letter are municipal water supply plants)

during the last ice age some 10,000–20,000 years ago, now containing usually sandy, gravel and stone layers. The remainder of the water sources are situated in moraine or sandy areas. A water sample was taken from each water supply plant in four consecutive sampling rounds: autumn 2002, spring 2003, autumn 2003 and spring 2004, in seasons when it was believed that the risk of contamination of the groundwater could be the highest. The samplings were done in autumn (October–November) after the growing season before snow covered the ground and in spring (late March–May) after the ice melt, before the start of the growth period.

A total of 40 l of water were taken at each sampling from each water supply plant into sterile bottles and plastic containers from raw water, before any treatment (potential pH adjustment and disinfection) and transported to the laboratory for analysis of microbiological and physico-chemical water quality. After the sampling point, the distributed water of suppliers 2, 9, 14, 15, 17, 18 and 19 was disinfected with UV, while the water of supplier 7 was disinfected with chlorine. The other 12 water suppliers of 20 did not utilize disinfection or any other water treatment except for pH adjustment after the sampling point.

The on-site hazard identification was conducted at each water supply by visiting the plant in conjunction with the samplings together with the person in charge of the water supply maintenance. A questionnaire form about the hazards to water quality with scored multiple-choice answers was completed. The scores given to answers were weighted in relation to the probability of the hazard occurrence and to the severity of microbial water safety reduction. The estimated hazards included (the scores of multiple-choice answers in the parenthesis):

- topography near the water supply well (1, 2, 6),
- possibility for surface water runoffs (1, 5, 9),
- the possibility of uncontrolled river or lake bank filtration (0, 1, 3, 5, 7),
- occurrence of sand and gravel mining sites nearby (1, 2, 3, 6),
- an insufficient depth of protective soil layers above the water table (1, 2, 5, 9),
- roads nearby (0, 1, 2, 3, 5),
- agricultural activities nearby (0, 1, 5, 9),
- sewerage nearby (1, 3, 5, 9),
- inhabitation with sewage treatment activities nearby (0, 1, 3, 5) and
- ditches nearby (0, 3, 5).

From answers to the questions, the total sum of scores was calculated for each water supply. The minimum total score of on-site hazards for the supply was 5 (no hazards identified, but some of the hazards were estimated to never be completely absent) and the theoretical maximum was 70

(all hazards estimated to be present at the highest level). The on-site hazard identification was supplemented with a review of related background material such as the maps of the sites, previous compliance monitoring results and evaluation of the overall state of the water works construction and maintenance. These observations were considered when associations between water supply characteristics and water quality parameters were defined but not included into the total score of on-site hazards.

Microbiological Water Analysis

The water samples were kept in a cool box and transported immediately to the laboratory, where the microbiological analyses were started on the same day or no more than 24 h after sampling.

The counts of faecal indicator bacteria (*E. coli*, intestinal enterococci, *Clostridium perfringens*) and other indicator microbes (coliform bacteria, heterotrophic plate count, total cell count, DNA coliphages and male-specific coliphages) were analysed, and the presence of selected pathogenic microbes (noroviruses, thermotolerant *Campylobacter* spp., Enterohaemorrhagic *E. coli* (EHEC), *Listeria* spp., *Yersinia* spp. and *Salmonella* spp.) was tested. In addition to the standard water microbiological analysis, enhanced methods utilizing sensitive cultivation media, tenfold water volumes and prolonged incubation were applied.

Escherichia coli and coliform bacteria were analysed as described elsewhere (Pitkänen et al. 2007) with membrane filtration method using the international standard LTTC method (ISO 9308-1 2000) and Chromocult® Coliform Agar (CC) (Merck, Darmstadt, Germany) or the MPN method Colilert®-18 with 51-well Quanti-tray® (Colilert) (IDEXX Laboratories, Inc., Maine, USA). The sample volumes were 100 and 1,000 ml on each media and in cases when no colonies were detected after 24 h of incubation, the incubation was extended up to 48 h. Intestinal enterococci were determined on Slanetz & Bartley medium (Oxoid, Basingstoke, UK) from 100 and 1,000 ml sample volumes using the standard method (ISO 7899-2 2000) and in cases when no colonies were seen after 48 h of incubation, the incubation was continued up to 72 h. *C. perfringens* was tested from the 100 ml sample on mCP medium (Oxoid, Hampshire, UK) according to European Union (1998).

The heterotrophic plate count (HPC) was determined by spread-plating on R2A medium (Difco, Sparks, MD, USA) (Reasoner and Geldreich 1985) according to the standard methods for HPC, 9215 (Greenberg et al. 1995). Additionally, HPC was analysed using yeast extract agar (YEA, LabM, Lancashire, UK) and membrane filtration of 1, 10, 100 and 1,000 ml of water instead of the pour-plate technique (ISO 6222 1999). Total cell counts were counted as

acridine orange direct counts (AODC) (Hobbie et al. 1977) with an Olympus BH-2 epifluorescence microscope (Olympus Optical Co., Tokyo, Japan).

The DNA-coliphages and male-specific coliphages were determined from 3 × 500 ml samples using the EPA two-step enrichment procedure (EPA 2001) with hosts *E. coli* ATCC 13706 and ATCC 15597 in autumn 2002 and since that time both *E. coli* ATCC 13706 and ATCC 700609 for somatic phages as well as ATCC 15597 and ATCC 700891 for male-specific coliphages. Nalidixic acid was used with the host ATCC 700609 and ampicillin with the host ATCC 700891.

Noroviruses were determined from the samples taken from autumn 2002 to autumn 2003. 1,000 ml of sample was concentrated using positively charged membrane filtration, and then the filters were eluted using beef extract solution (Gilgen et al. 1997; Kukkula et al. 1999). RNA was extracted from 100 µl of microconcentrated eluates, and noroviruses were analysed using the primers and RT-PCR protocol as described by Vinjé and Koopmans (1996) and Kukkula et al. (1999).

In the analysis of bacterial pathogens, water samples were filtered through a 0.45-µm membrane filter (Millipore, Bedford, USA). For *Campylobacter*, the sample volume was 3,000 ml, and the other pathogens were tested from 1,000 ml volume of water.

Thermotolerant campylobacteria were tested according to the international standard method ISO/DIS 17995 (2005) using Bolton broth (LabM, Lancashire, UK), Preston broth and mCCDA medium (Oxoid, Hampshire, UK) in micro-aerobic conditions (Campygen, Oxoid).

The determination of EHEC was achieved by incubating the filter overnight in 50 ml of MTSB with 20 mg/l novobiocin (Lab M). A loopful of the enrichment broth was transferred on SMAC agar (Oxoid) and incubated overnight at 37°C prior to PCR employed to detect *stx1* and *stx2* genes (Paton and Paton 2002). In addition to the enrichment method, *E. coli* isolates from analyses of *E. coli* and coliform bacteria were tested accordingly.

For detection of *Listeria* spp., UVM I and then in UVM II enrichment broths (Oxoid) were utilized, both at 30°C for 24 h, and finally broth was cultured to Palcam (Oxoid) and blood agar plates and incubated in 5% CO₂ at 37°C for 48 h.

For detection of *Yersinia* spp., the filter was incubated in 50 ml of tryptone soya (TS) broth at 20°C for 18 h prior detection by PCR, direct culture and cold enrichment methods. DNA was isolated using Instagene (Biorad, California, USA) and analysed for *Yersinia* by *yadA* (Kapperud et al. 1993) and *ail* PCRs (Thisted Lambertz et al. 1996). Direct culture on CIN agar (Oxoid) was incubated at 30°C for 18 h and in the cold enrichment, TS-broth was diluted 1:10 in TS broth and kept at 4°C for 21 days and plated onto CIN agar plate.

Salmonella was detected using RVS enrichment method (NMKL 71 1999) utilizing XLD (LabM, Lancashire, UK) and Önözü (Merck, Darmstadt, Germany) agar plates at 37°C for 18 h after enrichment.

Physico-Chemical Water Analysis

The temperature, pH and electrical conductance of waters were analysed during the sampling with portable equipment using pH 340 and LF-30 probes (WTW, Weilheim, Germany). Water samples for other physico-chemical analyses were frozen at −20°C and analysed within the next 3 months.

Nitrate, nitrite, chloride and sulphate were measured with standard methods (ISO 10304-1 1992) as well as the chemical oxygen demand (COD_{Mn}) (SFS 3036 1981). The molecular size distribution of natural organic matter (humic fractions) was analysed using a high-performance size exclusion chromatography method (HPSEC) and presented as peak areas of different molecular size fractions (Vartiainen et al. 1987; Lehtola et al. 2003). Total phosphorus was measured spectrophotometrically (SFS-EN 1189 1997), and total non-purgeable organic carbon was assayed by a high temperature combustion method with a Shimadzu 5000 TOC analyser (Kyoto, Japan) (SFS-EN 1484 1997).

Statistical Analysis

Prior to the statistical analyses, <10 CFU/ml (R2A) and <1 CFU/ml (YEA) HPC results were converted to be 5 and 0.5, respectively (half of the detection limit). Non-parametric methods were used, because normal distributions of the variables could not be obtained by standard transformations. Spearman rank correlation was used to analyse correlations between water supply characteristics and water quality parameters. Differences in the occurrence of dichotomous variables between water supply characteristics and water quality parameters were examined with χ^2 test and Fisher's exact test. Difference in coliphage positivity between sampling times was analysed with Kruskal–Wallis test. The concentrations of coliform bacteria were compared between analytical procedures using Wilcoxon signed-rank test. Wilcoxon rank-sum test was used to compare differences in total cell counts in spring and autumn samples. McNemar test was used to evaluate the difference between paired proportions of male-specific coliphages and somatic coliphages. The average concentrations of heterotrophic bacteria and physico-chemical parameters were reported as geometric means (GM) and geometric standard deviations (GSD). The associations between the observed hazards to water quality, water supply characteristics and different water quality parameters were

analysed using crosstabs and regression models. Logistic regression models were used to calculate odds ratios (OR) for faecal contamination and for the presence of coliform bacteria. Linear regression was used for the calculation of coefficients of determination for HPC and for nitrite concentration after logarithmic transformation. SPSS for Windows, version 15.0.1 (SPSS Inc., Chicago, USA) and SAS statistical package version 8.2 (SAS OnlineDoc®, SAS Institute Inc., Cary, NC, USA) were used for these analyses.

RESULTS

The Results of Microbiological Analysis

In one sample obtained from the water supply 7 *Yersinia enterocolitica* serotype O6 was detected. Thermotolerant campylobacteria, noroviruses, EHEC, *Listeria* spp. or *Salmonella* spp. were not detected in any of the water samples analysed. Faecal indicator bacteria (*E. coli*, intestinal enterococci or *C. perfringens*) were found in 8 of total 80 studied groundwater samples originating from five different water supply plants (Table 2).

Escherichia coli was identified once in supplies 1 and 6 (62 CFU/100 ml and 0.1 CFU/100 ml, respectively) and twice in water supply 7 (first 1 CFU/100 ml and then 58 CFU/100 ml). Intestinal enterococci were detected once in water supply 1 (0.1 CFU/100 ml), once in water supply 5 (0.1 CFU/100 ml) and once in water supply 7 (0.9 CFU/100 ml). In the samples from water supply 20, intestinal enterococci were detected twice (first 0.1 CFU/100 ml and then 23 CFU/100 ml). *C. perfringens* was detected in one sample from water supply 7 (0.4 CFU/100 ml).

Overall, 40% of the samples (32 of 80) were positive for coliform bacteria and positive samples originated from 12 different water supply plants. In water supplies 1, 12 and 18, all four samples tested were positive for coliform bacteria. Both the tenfold increase of sampling volume and the twofold extension of incubation time increased the bacterial counts significantly ($P = 0.031$ and $P < 0.001$, respectively). The CC medium resulted in more positive findings than the LTTC medium ($P < 0.001$).

In all, 59% of the samples (47 of 80) contained phages, which were detected at least once from all water supply plants. Samples from water suppliers 7 and 11 were most frequently positive for phages. There was a significant season-associated difference in the frequency of coliphage positive samples ($P < 0.001$), and the positive findings were more frequent in the autumn 2002 and spring 2003 than during the latter two samplings. Male-specific coliphages were found more often than somatic coliphages (29 and 5.1%, respectively; $P = 0.003$).

The HPCs were higher on R2A medium than on YEA medium, the GM being 114 and 1 CFU/ml, respectively, though there was no clear seasonal difference. R2A resulted in counts above the detection limit of the method (for R2A 10 CFU/ml and for YEA 1 CFU/ml) more often than YEA ($P = 0.037$). The maximum HPC was 21,400 CFU/ml on R2A medium and 108 CFU/ml on YEA medium, these being detected in the spring of 2004 from the sample of water supply 12.

The GM of AODC was 53,500 cells/ml with a maximum of 387,000 cells/ml in water supply 5. Also in samples of water supplies 2 and 6, high counts were observed: the GM of AODCs was over 100,000 cells/ml and maximum counts of both supplies were higher than 200,000 cells/ml. There was a significant difference between the AODCs in spring and autumn samples ($P = 0.021$), i.e. the numbers were higher in autumn samples.

Physico-Chemical Results

The major non-compliance of the physico-chemical water quality was the exceeding of the quality criterion related to the nitrite concentration. The limit value for tap water (0.50 mg/l) was exceeded once: in water supply 1 in the spring of 2003 (0.59 mg/l). The European Union (1998) parametric value for nitrite in raw water (0.10 mg/l) was exceeded in 13 of 80 samples originating from 12 water supply plants (Table 2). Most of the non-compliance occurred during the sampling conducted in the autumn of 2003.

The highest nitrate concentrations were in water supplies 7 and 16, GM of four samplings were 15.1 ± 1.6 and 26.7 ± 1.2 , respectively. The organic matter content measured as COD_{Mn} exceeded once the parametric value of 5.0 mg/l at the water supplier 5 in the autumn 2002. The same water supplier produced also the highest mean concentration of total non-purgeable organic carbon (1.7 mg/l in all samplings). The sum of peak areas of the humic fractions representing the total amount of natural organic matter ranged from 4,810 to 43,900. The lowest detected sum of peak areas originated from water supply 4 in spring 2003, and the highest value was detected during the same sampling round from the water of the water supplier 5. Water supply 7 exhibited the highest phosphorus concentrations and also three other water supplies (1, 4 and 13) had more than 10 µg/l phosphorus in three or four samplings.

Scores of On-site Hazard Identification

Figure 1 illustrates the scores of on-site hazards defined at each supplier. The highest scores of hazards (the total score

Table 2 Summary of observed microbial and physico-chemical water quality hazards in four consecutive sampling rounds and total scores given to observed on-site hazards at each water supply plant (min–max: 5–70)

Water supply	Observations of faecal bacteria	Counts of other microbes	Physicochemical quality	Total score of on-site hazards
5	Enterococci in 1,000 ml, after 72 h (III)	Coliforms (I, III, IV) and coliphages (I, II, III) present, high HPC (I, II, III, IV) and AODC (I, III, IV)	The highest concentration of organic matter (I)	19
18	–	Coliforms (I, II, III, IV) and coliphages (I, II, III) present	–	19
4	–	Coliforms (III, IV) and coliphages (I, II) present, high HPC (I)	High nitrite (III) and phosphorus concentration (I, II, III, IV)	24
6	<i>E. coli</i> in 1,000 ml (III)	Coliforms (I, III, IV) and coliphages (II, III, IV) present, high HPC (I, II, III, IV) and AODC (I, II, III)	High nitrite concentration (III)	24
15	–	Coliphages present (I, II)	High nitrite concentration (III)	25
20	Enterococci in 100 ml (III, IV)	Coliforms (III, IV) and coliphages (I, III) present, high HPC (II, IV)	High nitrite (III) and phosphorus (II) concentration	25
11	–	Coliphages present (I, II, III)	–	31
14	–	Coliforms (I, III) and coliphages (I, II) present, high HPC (III)	High nitrite concentration (III)	31
12	–	Coliforms (I, II, III, IV) and coliphages (I, III) present, high HPC (I, IV)	–	32
19	–	Coliphages present (I, II, III), high AODC (III)	High nitrite (III) and phosphorus (III) concentration	34
2	–	Coliphages present (II, III), high HPC (II) and AODC (I, III)	High nitrite concentration (IV)	36
3	–	Coliforms (III) and coliphages present (II, III), high HPC (I) and AODC (I, II)	–	36
16	–	Coliphages present (II, III, IV), high HPC (II)	High nitrate concentration (I, II, III, IV)	37
8	–	Coliphages present (II, III)	High nitrite concentration (III)	38
17	–	Coliphages present (I, II)	–	39
13	–	Coliforms (I, IV) and coliphages (I, II, III) present, high HPC (III)	High nitrite (III) and phosphorus (I, II, III, IV) concentrations	40
7	<i>Y. enterocolitica</i> detected (IV), <i>E. coli</i> in 100 ml (III, IV), enterococci in 1,000 ml (III), <i>C. perfringens</i> in 1,000 ml (IV)	Coliforms (I, III, IV) and coliphages (I, III, IV) present, high HPC (I, II, III, IV) and AODC (IV)	High nitrate (I, II, III, IV), nitrite (III) and phosphorus (I, II, III, IV) concentrations	44
1	<i>E. coli</i> in 100 ml (IV), enterococci in 1,000 ml (III)	Coliforms (I, II, III, IV) and coliphages (I, III) present, high HPC (I, II, IV) and AODC (I, III, IV)	The highest nitrite (II, III) and high phosphorus (I, II, III) concentrations	45
9	–	Coliforms (III, IV) and coliphages (III) present, high AODC (I, III)	–	45
10	–	Coliphages present (I, II)	High nitrite concentration (III)	45

– Not observed or low concentration. Observation from: I = autumn 2002, II = spring 2003, III = autumn 2003 or IV = spring 2004 samples. *HPC* heterotrophic plate count, high if >8 pmy/ml on YEA medium or >250 pmy/ml on R2A medium; *AODC* acidine orange direct count (total cell count), high if >85,300 cells/ml. Concentration of nitrate considered high if >9 mg/l, of nitrite if >0.1 mg/l, and of phosphorus if >10 µg/l

was 44–45 of 70) were obtained from water suppliers 1, 7, 9 and 10. At two of these supplies with the highest total score (supplies 9 and 10), no indication of fresh faecal contamination was detected, but coliforms, coliphages and/or nitrite were present in their raw water (Table 2). At the other two (supplies 1 and 7), the raw water proved to be faecally contaminated; *E. coli* in 100 ml was detected among other faecal bacteria, and there were coliforms, coliphages and nitrite present as well. At three other water supplies (5, 6 and 20) of this study, where faecal indicator bacteria, but not *E. coli* in 100 ml, were present, the given total score of on-site hazards were relatively low (Fig. 1; Table 2): 19, 24 and 25 of 70.

All seven water supplies with UV disinfection equipments were municipally owned and had no findings of faecal indicators in their raw waters during the study, but one (supply 9) had the highest total score of on-site hazards (Fig. 1). The water supply plant applying chlorination was operated by water cooperative (supply 7), and the disinfection was essential measure since faecal indicator bacteria and *Yersinia enterocolitica* were detected from the raw water of that supply.

The most common hazard identified in the suppliers and classified to reduce water quality was poor well construction enabling surface water to gain access to a well in conjunction with rainfall or flooding (Fig. 1). The majority, 13 of 20 suppliers were awarded the maximum hazard score for surface water runoffs. The second most common identified hazard was an insufficient depth of the protective layer above the water table. In water supply 1, the water table was almost as high as ground level, but also at 14 other supplies the protective layer was considered to be insufficient (only 2–5 m). The third main hazard was land

use for agriculture and animal grazing in the vicinity of the groundwater abstraction wells. Four suppliers (3, 11, 13 and 19) received the highest score for agricultural hazards, and also five other supplies were situated close to agricultural activities (1, 7, 9, 10 and 16).

The other identified hazards classified to significantly increase the risks for water safety included bank filtration (the main hazard at water supply 5 and present at supplies 2, 4, 9, 10 and 14) and municipal sewerage networks (present near to supplies 8 and 17 as well as to 12, 18 and 19). In addition, inhabitation with their own sewage treatment activities was present close to most of the supplies (Fig. 1). Other hazards identified but regarded as more insignificant with respect to water quality in the studied sites included ditches (present close to nine supplies), sand and gravel mining (present in the vicinity of five supplies) and roads (present near to four supplies).

Parameters Associating with the Faecal Contamination

The observed associations between the water supply characteristics and water quality parameters are presented in Table 3. The depth of the protective soil layer above the groundwater table was less than 5 m in the majority of the studied water supplies which associated with the presence of *E. coli*, intestinal enterococci and with coliform bacteria.

Previous non-compliance in water quality (*E. coli*, enterococci or coliform bacteria detected in routine water quality monitoring) associated with faecal contamination and with high HPCs detected during the study, but the association was not statistically significant. The overall state of the water works construction and maintenance in

Fig. 1 The scores of on-site hazards estimated during the hazard identification procedure conducted at the studied water suppliers. * Water supplies applying disinfection after the sampling point

Table 3 Associations observed between the selected water supply characteristics and water quality parameters using crosstabs and regression analyses

Characteristics	The association observed
Depth of the protective soil layer above the groundwater table	The thinner the protective layer, the more frequent the findings of faecal bacteria and coliform bacteria ($P = 0.049$ and $P = 0.027$, respectively)
State of water works construction and maintenance	The supplies that were evaluated to need improvement in their construction or maintenance had higher coliform bacteria counts and heterotrophic plate counts in comparison to the supplies where improvements were not considered necessary, OR = 6.8 (2.1–26.4) and OR = 4.1 (1.5–12.2), respectively
Size of the water supply plant (number of persons served <1,000 or $\geq 1,000$)	All supplies with faecal findings (<i>E. coli</i> or intestinal enterococci) served less than 250 persons The smaller supplies had more coliform bacteria findings, OR = 3.0 (1.1–8.0) and higher heterotrophic plate counts on YEA medium ($R^2 = 0.164$, $P < 0.001$) than the supplies serving more than 1,000 persons
Type of water supply management (municipally owned or water cooperative)	All findings of faecal microbes (<i>E. coli</i> or intestinal enterococci) were detected in supplies managed by water cooperatives Water cooperatives had also more findings of coliform bacteria and had higher heterotrophic plate counts on YEA medium ($R^2 = 0.062$, $P = 0.025$)
Quantity of water in the aquifer	The better quantity, the smaller risk of <i>E. coli</i> or intestinal enterococci presence ($P = 0.035$) Negative association with heterotrophic plate counts on YEA medium ($R^2 = 0.048$, $P = 0.051$)
Physicochemical quality	Nitrite had positive association with faecal contamination (presence of <i>E. coli</i> or intestinal enterococci), $R^2 = 0.103$, $P = 0.004$, and with non-faecal microbiological indicators (coliform bacteria, coliphages, heterotrophic plate counts and total cell counts), $R^2 = 0.104$, $P = 0.015$ If the overall physicochemical quality was not good, there was a higher risk for the presence of <i>E. coli</i> or intestinal enterococci, OR = 6.0 (1.4–29.5) compared to the situation when especially nitrite, total organic carbon and total phosphorus concentrations were lower

Odds ratios (OR) presented with 95% confidence limits

contrast did have a significant association with high counts of coliform and heterotrophic bacteria.

Sampling time seemed to affect the water quality results since all findings of faecal microbes (*E. coli* or intestinal enterococci) were detected during two latter samplings. The presence of coliform bacteria was more infrequent in the spring of 2003 than at other sampling times ($P = 0.048$), and nitrite concentrations were higher in the autumn of 2003 than during other sampling times. Irrespective of the fact that the study years had low precipitation and there were no severe rainstorms or floods occurring during the sampling campaigns (Finnish Meteorological Institute, 2002–2004), the weather observations supported the faecal findings: autumn 2002 and spring 2003 were drier than average, and no faecal microbes were detected at these times. In the autumn of 2003 and in the spring of 2004, the precipitation was more average after the dry year, and then faecal microbes were present in the waters. The time of the year may also affect the water quality results: in this study more findings of faecal microbes (*E. coli* or intestinal enterococci) and coliform

bacteria were detected in the autumn than in the spring, OR = 1.8 (0.4–7.9) and OR = 1.9 (0.8–4.7), respectively.

All samples with faecal indicator bacteria originated from water supplies serving less than 250 consumers. The water supplies organized by water cooperatives were on average smaller than municipally owned supplies. However, there was no difference in the total score of on-site hazards or in the prevalence of agricultural activities between the smaller and larger suppliers. Bank filtration was more common in larger supplies and smaller supplies encountered the risks of surface water run-offs more often, but these observations were not statistically significant. In addition to the water supply characteristics, faecal contamination was associated with sampling time and with the concentrations of nitrite, total organic carbon and total phosphorus. Moreover, the presence of coliform bacteria and HPCs was apparently associated with water supply characteristics: size, management type and water quantity (Table 3), and their presence also displayed a positive connection with faecal contamination.

DISCUSSION

Our data showed that faecal contamination indicated by the appearance of faecal indicator microbes was present in 5 of 20 studied raw waters of groundwater supplies in central Finland. These supplies were all small, serving less than 250 persons. This fact suggests that the smallest water supply plants, often managed by local water cooperatives, encounter more problems (both microbiological and physico-chemical) in their water quality than the municipal water supply plants, which on average are larger water production units. It has been recognized also worldwide that small water supply plants, not only in developing countries but also in the developed ones, suffer the serious limitations of funding, personnel and knowledge (WHO 1997; Ford et al. 2005; Hulsmann 2005).

In Finland, almost half of water supply plants are managed by local water cooperatives and the other half by municipals (Lapinlampi and Raassina 2002). This means that there are over 600 water cooperatives located in less populated areas and villages all over Finland, which may be at risk in terms of the water quality. Most of the waterborne outbreaks in Finland have occurred in private water systems or in the small groundwater supply plants (Miettinen et al. 2007). In other European countries, faecal contamination has also been identified as a major problem encountered in small groundwater supplies even though systematic information on the extent of waterborne infections is lacking (Hulsmann 2005; Hamsch et al. 2007). However, no intestinal pathogens except for a non-virulent strain of *Yersinia enterocolitica* in one sample were detected in this study, and there were no reports of any gastrointestinal symptoms experienced by the water consumers.

Multiple hazards impacting on water safety were identified at the studied water supplies. The main hazard identified to reduce water safety in this study was insufficient protection against influence of surface water enabling surface water to gain access to the well. This observation confirms the previous reports of runoffs as a cause leaching faecal material directly to the raw water wells of small groundwater supplies (Kay et al. 2007; Isomäki et al. 2008; Richardson et al. 2009). Even though water cooperatives seemed to have lower water quality than municipally owned supplies, this might be associated more with differences in supply construction and maintenance or with the hydrogeological aspects in abstraction area rather than with the type of water supply management.

The high score of on-site hazard does not mean that at the moment of sampling, water is contaminated and a low score does not completely safeguard from contamination. The presence of a single risk, if it is serious enough such as insufficient well construction (Photograph 1) or

uncontrolled bank filtration (Photograph 2), might lead to contamination. In this study, hazards to water quality were identified to be present at all the studied 20 community water supplies; the given total score of on-site hazards varied from 19 to 45. Correspondingly, there were also more or less findings of microbial or chemical water quality indicators in the raw waters; coliphages, if nothing else, were detected from the cleanest water supplies. However, it is difficult to determine a quantitative relationship between detected indicator concentration and the degree of public health risk (Hrudey and Hrudey 2004).

In our work, the on-site hazard identification and weighting contained in part the same elements as the water microbiological vulnerability indicator system used by Cool et al. (2010). However, the weighting of scores given to hazards needs to be performed carefully. In this study, the weighting was done based on the judgements of experts. In the future, the multi-criteria analysis method proposed by Joerin et al. (2010) might serve as useful tool in the assessment of source water susceptibility to microbiological contaminations in rural groundwater watershed areas.

Agricultural activities considered beforehand to have a major impact on the microbial contamination of groundwater were found not necessarily to pose a threat to water supply plants as only 2 of 9 supplies with high score on agricultural activities had faecal microbes present in their raw waters during the study. In conjunction with the faecal indicator microbes, the elevated concentrations of nitrite, total organic carbon and phosphate-phosphorus were detected in our study. Research findings supporting a link between nutrients and faecal contamination have been previously reported elsewhere (e.g. Fernandez-Molina et al. 2004; Schoonover and Lockaby 2010; Pronk et al. 2007; Boyer and Neel 2010). Large rural areas in central Finland are important cattle breeding areas with intensive farming producing large amounts of faecal material. It is known that there could be leakages of faecal microbes and nutrients such as nitrate and nitrite from cattle herds into the groundwater aquifers (Maticic 1999; Heinonen-Tanski and Uusi-Kämpä 2001; Saarijärvi et al. 2004).

It is also possible that human excreta may leach into groundwater since there are rural areas having tap water, but being in lack of sewerage networks. Thus, private septic tanks, sewage ponds, etc. may cause sewage penetration into groundwater sources in rural areas (Cool et al. 2010; Schijven et al. 2010). In our study, sewage treatment activities were present close to 4 of 5 water supply plants with the findings of faecal bacteria, but those activities situated also close to 11 water supplies where faecal bacteria were not detected. The heterogeneity of sewage treatment processes and of soil characteristics complicates the establishment of a link between sewage treatment

Photograph 1 A typical water supply well situated near to a sand mining site in central Finland. Photo: I. Miettinen

activities and faecal contamination (Schijven et al. 2006, 2010). Therefore, more detailed description of the hydrogeological characteristics nearby the groundwater wells would have assisted the assessment of the vulnerability of the studied water supplies. Also sand and gravel mining sites situated in the vicinity of the groundwater abstraction wells were identified as hazards in this study but they did not associate with any notable faecal contamination in the study period.

The representativeness of the sampling is one of the factors affecting to the detection or non-detection of faecal contamination of a water supply. During this study, after the detection of faecal contamination, the local authorities were informed as soon as possible. The main action taken after our findings was re-sampling. We did not collect all the information about the responses, but at least in some cases it is known that re-sampling did not detect any contamination, indicating that the contamination was a transient phenomenon. This is in accordance with the findings of a simulation model study, where the mean probability that standard monitoring programmes would detect faecal contamination was estimated as only about 5% (Van Lieverloo et al. 2007). In our present study, some of the faecal contaminations would have remained undetected if a tenfold volume of the sample and a prolonged incubation time had not been employed and this may

explain why there was non-detection in re-sampling. However, 2 of 4 *E. coli* findings originating from water supplies with a high total score of on-site hazards and 1 of 5 intestinal enterococci findings would have been detected also with conventional procedures utilized in routine monitoring. Thus, in compliance monitoring, the 100 ml volumes may be sufficient (Locas et al. 2008). For hazard identification purposes and in cases where there is a suspicion of waterborne illness transmission, however, larger volumes are often needed (Hänninen et al. 2003).

It has been suggested that water supplies should implement a systematic risk management (Water Safety Plan Approach, Davison et al. 2006) to ensure the safety of the drinking water and to prevent outbreaks of waterborne illness (Kay et al. 2007). Even though the financial resources at small community water supplies are limited, it has been calculated that the benefits of better management leading to prevention of waterborne illnesses certainly outweigh the costs of the improvements (Hunter et al. 2009). One of the key components of water safety plans is water supply system assessment including hazard identification and upgrading of the system in case that the capacity to meet health based targets is not even theoretically possible (WHO 2004). The present study shows that the preparedness against faecal contamination cases by terms of applying disinfection before distributing the water is not

Photograph 2 A water supply well situated near to a lake shore in central Finland. Photo: I. Miettinen

fully in line with the identifiable water quality hazards. Four supplies of total five with observed presence of faecal indicator bacteria did not utilize disinfection as a preventive measure to avoid waterborne illnesses and thus pumped the contaminated water directly into their distribution network.

More attention and resources are needed to guarantee sufficient source water protection, and utilization of a systematic risk management should be recommended for all community water supplies. The limitations of financial resources should not block the improvements from happening since the present study confirms that the hazard identification and the upgrading of the water treatment system would be more than necessary in many of the small community water supplies in central Finland. Further site-specific identification of hazards and mitigation of microbiological risks, e.g. by utilizing disinfection, is needed at community water supplies.

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