Assessment of microbial infection risks posed by ingestion of water during domestic water use and full-contact recreation in a mid-southern African region

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Abstract A customised Water-related Quantitative Microbial Risk Assessment (WRQMRA) process was used to determine risk of infection to water ingested by users in the south-eastern Free State, South Africa. The WRQMRA consisted of an observed-adverse-effect-level approach (OAELA) and a quantitative microbial risk assessment (QMRA). The OAELA was based on the occurrence of *E. coli* in the study waters to determine the *possible* risk of infection and the QMRA *probable* risk of infection by salmonellae. The WRQMRA was applied to recreational surface resource waters as well as waters from an unprotected spring and waters from the treated municipal supply that were stored in containers for domestic purposes. *E. coli* numbers were measured against expected infection levels expressed in water quality guidelines, while *Salmonella* counts were calculated to give the probable infection risk (P_i). *Ingestion* was based on intake volumes compiled for the various water uses. *E. coli* occurred in numbers $<10^6$ in the surface waters, while the untreated spring and treated supply water contained *E. coli* of $<10^2$ and $<10^1$ respectively. *Salmonella* occurred in numbers of $<10^3$ in recreational waters, and $<10^{-1}$ in water used for domestic purposes. A single exposure to the mean (as well as 95th percentile) risk was calculated using a β-Poisson dose-response model at ingestion volumes of 100 mL (for full-contact recreation) and 1,318 mL (for domestic water use). Both the OAELA and the QMRA approaches indicated a risk of infection to recreational and domestic water users, even for a single exposure event, with the OAELA either over- or under-estimating the risk of infection for singular exposure events. This indicated that this method, used on its own, could not reliably predict a realistic risk of infection. It is recommended that the full WRQMRA process be used, and further developed to address several uncertainties that became evident during this study.

Keywords *Escherichia coli*; observed adverse effect level; potable water; quantitative microbial risk assessment; recreation water; *Salmonella*

Introduction

Ingesting faecally polluted water has long been recognised as a primary cause of diarrhoea (Jagals, 1997; Genthe and Franck, 1999; DWAF, 2002). Predicting the risk of infection that can lead to waterborne diarrhoea should be part of managing the health-related microbiological quality of water (Haas *et al.*, 1999). This has become particularly important in developing countries. Current practices to predict a possible risk of infection related to the microbiological quality of water include environmental health practitioners and water-quality managers generally testing water for the presence of indicator microorganisms such as *E. coli*. If present, a negative health effect can be expected, with increasing risk expected as organism numbers increase. This approach can be referred to as an observed-adverse-effect-level approach (OAELA), based on the occurrence of microbiological indicator organisms instead of actual pathogens. It does not provide a quantitative value for the microbiological waterborne health hazards that threaten water users (Du Preez *et al.*, 2001), since it can, at best, indicate the risk of infection by diarrhoea-causing pathogens potentially occurring in the same water should a person ingest it. Indicator organism counts generally tend to underestimate water-related health risks (Genthe and Rodda, 1999). This

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may lead to underestimation of the *probability* that users, through ingestion of faecally polluted water, may be infected by diarrhoea-causing pathogens. By implication, this means that, e.g., *E. coli* can only indicate the *possible* risk of infection by pathogens. A more reasonable approach towards estimating (predicting) a *probable* risk of infection in people using microbiologically contaminated waters would be a quantitative microbial risk assessment (QMRA) based on actual pathogen numbers occurring in the ingestion water (Genthe and Rodda, 1999; Anderson, 2001).

This paper reports on a water-related quantitative microbial risk assessment (WRQMRA) process that applied an OAELA, as well as a QMRA, to determine a *probable* risk of infection posed by various water types in the Mangaung local municipal area (Middle-Modder River tertiary catchment, southeastern Free State, South Africa). Previous studies in the area (Jagals *et al.*, 1995; Jagals, 1997; Griesel and Jagals, 2002) reported that, based on indicator organisms, surface resource waters were often heavily faecally polluted by urban discharges posing a *possible* risk of infection to users. On the same indicator bases, municipal supply water, stored in containers by households, was also shown to pose a risk of infection from intestinal disease (Bokako, 2000; Nala, 2002). The WRQMRA process applied in this study consisted of both an OAELA and a QMRA. The OAELA was based on the occurrence of *E. coli* to determine the *possible* risk of infection, while the QMRA predicted the *probable* risk of infection by *Salmonella* in particular. The concepts of *possible* (indicator) and *probable* (pathogen) risk of infection were based on the "Weight-of-Evidence Class" classification used by Risk*Assistant™ (1995) for cancer research that classifies carcinogens according to their potential to cause cancer in humans. Carcinogens with higher potential to cause cancer are referred to as *probable* carcinogens, while *possible* carcinogens are less likely to cause cancer.

The key focus of this study was to assess the *probable* risk of infection by a pathogen. Nevertheless, applying the WRQMRA provided for comparison of the *possible* (OAELA) *vs* the *probable* (QMRA) risk of infection in the study area waters. This was to provide service providers in the area with a more realistic tool to assess the health risk posed by water.

Materials and methods

Water-use environments

The study was conducted in the Mangaung Local Municipal area that lies within the Middle-Modder River tertiary catchment in the southeastern Free State, South Africa. Two water-use environments were identified for this study: (a) the Renoster Spruit Quaternary Catchment (RSQC) and (b) water stored in household-containers. Within the RSQC, three sampling sites (RS1, RS2 and BP1) represented the health-related microbiological quality of water within this area. The respective *E. coli* and salmonellae data measured at each site were combined, and their means used as representative of the risk posed by the RSQC water. People fetched water from remote sampling sites F1 and C1 and stored it in containers at home for domestic purposes. F1 was an unprotected spring accessed from all surface-ends by humans and animals. C1 was a communal tap on a treated water-supply pipeline some distance from the study household.

Water-use activities

The untreated surface waters of the RSQC represented the risk posed by ingesting water during full-contact recreational activities. The container-stored drinking water represented the risk from domestic water use (e.g. ingestion).

Water-related quantitative microbiological risk assessment (WRQMRA)

To determine a probable risk of infection, a WRQMRA was customised to include the

OAELA and QMRA. The OAELA (*possible* risk of infection) compared occurrence of *E. coli* in the study waters to various guideline-limits for the water uses (DWAF, 1996a,b) and then assumed co-occurrence of associated pathogenic microorganisms. Depending on the *E. coli* levels, no or low, medium and/or high adverse health effects (gastrointestinal disease, e.g. diarrhoea) might be observed in groups that ingested the water. The QMRA (*probable* infection risk (P_i)) was based on the occurrence of salmonellae and calculated P_i through exposure- and dose-response assessment, as well as risk characterisation. Exposure assessment comprised four steps.

1. *Water ingestion:* as the exposure route.
2. *Ingested water* volumes based on involuntary (during recreation and other domestic-related purposes such as body washing), as well as intentional (drinking the water for survival), ingestion. Limited resources prevented investigating actual ingestion volumes, e.g. duration and frequency of a particular (domestic or recreational) water use event or activity. Instead, documented ingestion volumes from local and international studies were collated and applied (Table 1). *Involuntary ingestion volumes* focused on 100-mL water ingested during full-contact recreation. Table 1 summarises the range of involuntary ingestion volumes (based on water contact) used for the whole study.

   Intentional ingestion volumes (daily intake/person in Table 2) were approached differently. Various authors use an adult water ingestion rate of 2,000 mL/person/day (mL/p/d) based on human feeding studies (Haas *et al.*, 1999; Haas and Eisenberg, 2001). The applicability of this ingestion rate was questioned for this study, since the target households consisted mainly of poor families living in sub-standard housing with varying levels of access to water supply. Dose was based on intake volumes modified to reflect South African conditions (Bourne *et al.*, 1987, 1992; Theron, 2000). Table 2 contains an international age-grouping from Roseberry and Burmaster (1992). The infantile ingestion volume of 1,318 mL/p/d was used for this study, because the highest ingestion volume constituted the highest risk and infants are usually more prone to disease (Haas *et al.*, 1999).

Table 1 Involuntary ingestion volumes based on the intensity of water contact per event

Contact intensity	Full-body immersion	Intermediate	Other
Intake volumes	≤100 mL swallowed/event • DWAF, 1996b • WHO, 1998 • Genthe and Rodda, 1999 • Haas *et al.*, 1999	50 mL swallowed/ event • Medema *et al.*, 2001	10 mL accidental gulping • Genthe and Rodda, 1999 • Medema *et al.*, 2001
Events	• Social swimming activities • Sporting swimming, e.g triathlon • Children playing in water • Body-washing in resource water	• Repeated immersion during skiing, wind-surfing, canoeing	• Laundry • Fishing • Ingestion related to irrigation in agri- and horticulture (golf courses)

Table 2 Intentional daily ingestion volumes for South Africans

Water intake	Infants 0≤ age <1*	Children 1≤ age <11	Adolescents 11≤ age <20	Adults 20≤ age <65	Elderly 65≤ age
mL/p/d	1,318	630	773	952	865

* Mean ingestion compiled from 50th percentile weight/age (kg) clinic chart multiplied with mean ingestion of 150 mL/kg/d

3. *Microorganism numbers* were determined in water samples collected in sterile 500 mL Whirlpacks®, transported to the laboratory at <10°C and analysed within 6 h. *E. coli* (EC) were detected by membrane filtration (APHA, 1998) on Chromocult Coliformen Agar (Merck, 1996), dark-blue to violet colonies counted and expressed (CFU/100 mL). *Salmonella* were detected by the three-tube MPN technique (APHA, 1998) (pre-enrichment in Buffered Peptone Water and Rappaport-Vassilliades broth with plating on XLD agar; Oxoid). Black-centred red colonies were counted (CFU/100mL) and verified with Analytical Profile Index (API) 20 E multi-test galleries (bioMérieux®, 2000).
4. *Dose* was calculated from the *Salmonella* numbers detected in the respective waters and the hypothetical volumes of water shown in Tables 1 and 2.

Dose-response assessment. The β-Poisson dose-response model (Table 3) calculated the probability of Salmonellae infection (P_i) after a single exposure, based on dose-response parameters (α and N_{50}) for *Salmonella* infections (Haas *et al.*, 1999).

Risk characterisation

This study applied the USEPA (1994) maximum annual risk of enteric disease infection (P_i) of 10^{-4} or 1 case/10,000 persons/year for consumption of drinking water (Regli *et al.*, 1991). Risk was calculated at exposure to the mean as well as at the 95th percentile, and expressed as a fraction of 10,000 of the population as well as percentage (%) P_i. Various uncertainties identified throughout the study are discussed.

Results and discussion

Table 4 summarises the indicator and pathogen occurrence in the two water use areas for the summer 2001/02 period. The probabilities of Salmonellae infections (P_i) posed by full-contact recreation and domestic water use are shown in Table 5.

This section is not exclusively about whether a risk has occurred or not, but also to illustrate whether the QMRA approach could add value to the OAELA that environmental health practitioners would typically follow. To determine whether *E. coli* (OAEL

Table 3 The β-Poisson model and parameters for calculating probability of infection by *Salmonella*

Daily risk of infection (Haas and Eisenberg, 2001)	
$P_i = 1 - \left[1 + \frac{d}{N_{50}}(2^{\frac{1}{\alpha}} - 1)\right]^{-\alpha}$	P_i = probability (risk) of infection d = dose or exposure (number of Salmonellae) α = 0.3126 (parameter that characterises dose-response relationship) N_{50} = 23,600 (median infectious dose)

Table 4 *E. coli* and *Salmonella* numbers at the two water-use areas

Water-use areas and water types	Occurrence	Microorganism numbers (/100 mL)	
		E. coli	*Salmonella*
RSQC: Untreated surface water	Geometric mean	28,444	167
	Minimum	1,000	36
	Maximum	1,200,000	4,383
	95th percentile	213,786	883
Container-stored water: C1 treated municipal supply	Geometric mean	1.16	0.26
	Minimum	0.1	0.1
	Maximum	13,300	1,898
	95th percentile	138	497
Container-stored water: F1 untreated spring water	Geometric mean	104	0.28
	Minimum	7	0.1
	Maximum	25,300	584
	95th percentile	5,128	340

Table 5 Probability of *Salmonella* infection posed by full-contact recreation and domestic water use

Sample site	*Salmonella occurrence* (100 mL)		Expected dose	Probability of infection (P_i)	% P_i: Single exposure	Infections per 10,000 after single exposure
Recreation water (based on ingestion for full-body contact = 100 mL)						
RSQC	Geometric mean	167	167	0.0174	1.74%	174
	Minimum	36	36	0.0039	0.39%	39
	95th percentile	883	883	0.0801	8.01%	801
Domestic water (based on ingestion for infants = 1,318 mL)						
C1	Geometric mean	0.26	3.49	0.0004	0.04%	4
	Minimum	0.1	1.32	0.0001	0.01%	1
	95th percentile	497	6,550	0.3096	30.96%	3,096
F1	Geometric mean	0.28	3.70	0.0004	0.04%	4
	Minimum	0.1	1.32	0.0001	0.01%	1
	95th percentile	340	4,481	0.2540	25.40%	2,540

approach) would have predicted the occurrence of diarrhoeal disease in people, would have required a full epidemiological investigation based on deductions made from occurrence-and-effect. The USEPA provided an *E. coli* model to quantify the risk of infection for people exposed to recreational water by full-body immersion. According to this model, in areas where water, containing >1,000 *E. coli*/100 mL, was used, gastrointestinal illness could be expected to increase approximately in accordance with the following relationship (DWAF, 1996b):

$$y = -150.5 + 423.5\,(\log x)$$

where y = illness rate/100,000 persons and x = numbers of *E. coli*/100 mL ($x \geq 3$).

Although the formula was based on ingestion through full-body contact recreation, epidemiological studies have been based on similar principles for various water uses. For this study, this formula was used for the other water uses investigated as well, i.e. ingestion of water through intentional ingestion.

Figures 1–3 illustrate the seasonal, as well as mean single-event log *E. coli* and *Salmonella* counts at the two water-use areas for the 2001/02 summer. The figures also include the infection probability (P_i) for *Salmonella* based on an ingestion of 100 mL and

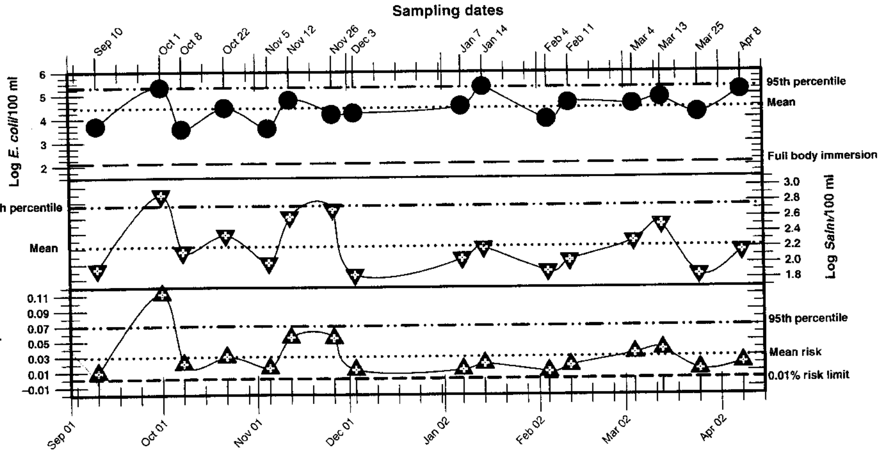

Figure 1 Risk posed by surface waters in the Renoster Spruit Quaternary Catchment

1,318 mL for full-body immersion recreational activities (e.g. swimming) and domestic water use (daily ingestion) respectively. The mean (dotted lines), as well as the 95th percentile (dot-dashed line) are used to compare risk of infection (short dashed line) for *E. coli* (OAELA) and *Salmonella* (QMRA). It is evident that *E. coli* occurred in numbers substantially above all the observed adverse effect levels (long dashed line). The 95th percentile risk, the mean risk, as well as several single-event risks posed by Salmonellae were above the USEPA (1994) acceptable risk limit.

For health protection, to predict health risk from a single event, high outliers portray the worst cases expected, since these would over-estimate rather than under-estimate the risk of infection for the whole season. On visual appraisal of the figures alone, it was not clear whether *E. coli* could reliably indicate the risk of *Salmonella* infection. High outlying values for both organism groups on 12 November 2001 and 13 March 2002 were used to calculate single-event risks for the untreated surface waters used for recreation in the RSQC (Figure 1). The mean *E. coli* occurrences for the two dates (based on an ingestion of 100 mL) did not differ by much (6.3 × 10^4 and 7.5 × 10^4 respectively). When applied in the USEPA formula, these occurrences calculated to a risk of gastrointestinal infections of 188 and 191/10,000 population respectively. However, when compared to the differences in the mean risk of *Salmonella* infection (100 mL ingested) on each of the specific dates, the

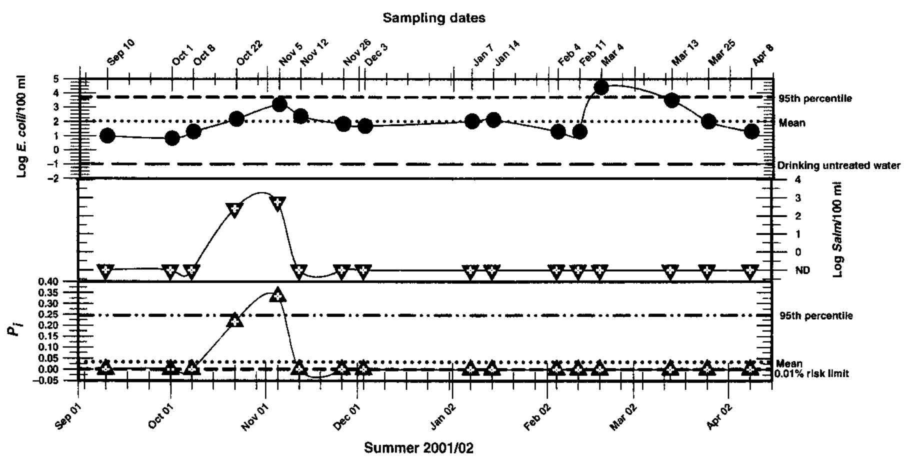

Figure 2 Risk posed by untreated fountain water sampled at F1

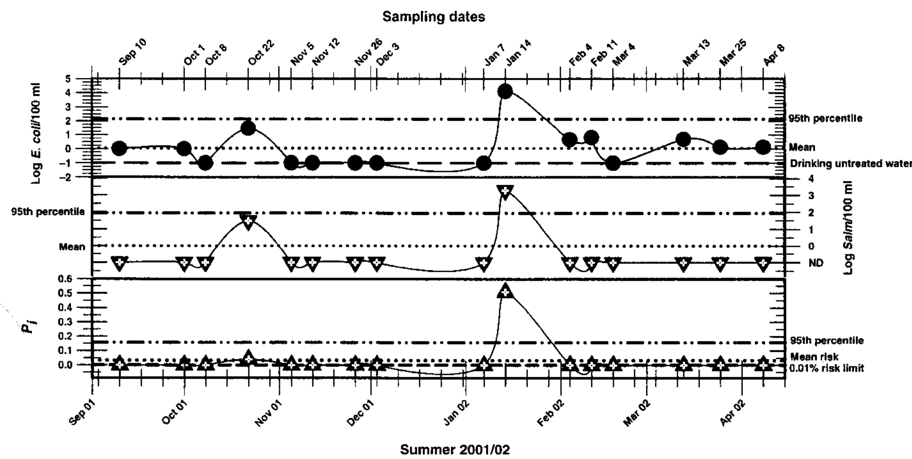

Figure 3 Risk posed by supply water stored in domestic containers

OAELA indicated a lower risk of infection – 12 November 2001 calculated as 552/10,000, and 38,410,000 on 13 March 2002). While both the OAELA and the QMRA indicated a risk of infection, the OAELA underestimated the expected cases, implying that environmental health practitioners using only *E. coli* data would have been unable to reliably predict the number of cases that clinic personnel in the area could expect. Figure 2 (5 November 2001 compared to 4 March 2001 and 13 March 2002) and Figure 3 (22 October 2001 and 14 January 2002) showed similar tendencies to either over- or under-estimate the probability of infection for the container-stored waters at an ingestion volume of 1,318 mL.

The QMRA predicted unacceptable risks and, while the OAELA also indicated risk, it tended to underestimate the risk and could not, with any degree of certainty, indicate the risk of infection by *Salmonella* on its own. The various factors that accounted for the uncertainty in the WRQMRA process are summarised as follows: (a) poor association between *E. coli* and Salmonellae implied that *E. coli*, while being an internationally accepted indicator of human entero-pathogens in water, should not be used to indicate the presence of single pathogens, such as Salmonellae, and the associated risk of infection; (b) both the OAELA and QMRA approaches indicated a risk of infection to users – from a cost-effectiveness perspective the OAELA was less costly, but it would depend on resources and other social circumstances whether a service provider would want to apply the full WRQMRA; (c) it was uncertain to what extent the results obtained from application of the USEPA (DWAF, 1996b) formula based on epidemiological studies for full-body contact recreation could be applied to compare the OAEL and the QMRA approaches for the other water-uses discussed; (d) modified ingestion volumes may not be entirely applicable because of the limited reference base for studies of this nature in South Africa; (e) as actual response after exposure (ingestion) was not measured in the study, the characterisation of the relationship of P_i was based on modelling – the actual infection rate was not measured by, for example, serum antibody increases or other inflammatory reactivity in human subjects; (f) the dose-response information (models and parameters) applied in this study were from international literature and may not have reflected the true probability of infection in South Africa or more specifically in the study area.

Conclusions

People, whether swimming in untreated surface waters or drinking treated or untreated water stored in containers in the area, were exposed to an unacceptable risk of infection. It is recommended that, in future, EHPs use the full WRQMRA process (both the OAEL and QMRA approaches), considering the uncertainties that developed throughout the study.

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