The importance of domestic water quality management in the context of faecal–oral disease transmission

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ABSTRACT

The deterioration of drinking water quality following its collection from a community well or standpipe and during storage in the home has been well documented. However, there is a view that post-supply contamination is of little public health consequence. This paper explores the potential health risk from consuming re-contaminated drinking water. A conceptual framework of principal factors that determine the pathogen load in household drinking water is proposed. Using this framework a series of hypotheses are developed in relation to the risk of disease transmission from re-contaminated drinking water and examined in the light of current literature and detailed field observation in rural Honduran communities. It is shown that considerable evidence of disease transmission from re-contaminated drinking water exists. In particular the type of storage container and hand contact with stored drinking water has been associated with increased incidence of diarrhoeal disease. There is also circumstantial evidence linking such factors as the sanitary conditions in the domestic environment, cultural norms and poverty with the pathogen load of household stored drinking water and hence the risk of disease transmission. In conclusion it is found that re-contaminated drinking water represents a significant health risk especially to infants, and also to those with secondary immunodeficiency.

Key words | diarrhoeal disease, household, hygiene, immunity, re-contaminated, water quality

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INTRODUCTION

The relative importance of water quality versus water quantity, sanitation and hygiene education interventions for protecting the population's health has been the subject of considerable debate (Esrey *et al.* 1985, 1991; Curtis *et al.* 2000). Nevertheless, there is broad agreement that good water quality, namely, free of pathogens, is important to human health.

World Health Organization (WHO) Guidelines, and most national drinking water standards, take the presence of *Escherichia coli* (*E. coli*) or thermotolerant coliforms as an indication of recent faecal pollution from human or warm-blooded animals (WHO 1993). Thus, the WHO guideline value of zero *E. coli* or thermotolerant coliform bacteria in any 100 ml sample of drinking water was established because even low levels of faecal contamination may potentially contain pathogens.

Given these clear and unambiguous guidelines, it is reasonable to conclude that drinking water exhibiting faecal contamination at any point in the distribution to consumption sequence should be cause for concern. However, it has been suggested that where drinking water becomes polluted during its collection and storage in the home it does not represent a serious risk of faecal-oral disease (Feachem *et al.* 1978; VanDerslice & Briscoe 1993).

This paper sets out to explore the potential health risk of consuming re-contaminated drinking water. A conceptual framework of the principal factors that determine the pathogen load of household drinking water is used to examine different scenarios of disease transmission. The paper draws on detailed observation of household water

management undertaken in recent field research in rural Honduran communities (Trevett 2003; Trevett *et al.* 2004).

TWO OPPOSING VIEWPOINTS

WHO guidelines make reference to the water supply situation common in many countries where water must be collected from a well or standpipe, transported home and then stored for domestic use. In such circumstances: 'Water that is transported or stored unhygienically may be recontaminated, which represents a public health risk… Most recontamination is the result of behavioural patterns; if these can be changed, the health risk can be reduced or eliminated' (WHO 1997). In their *Water Handbook*, UNICEF observe: 'There are many cases of water which is bacteria-free at the source becoming contaminated during transportation, storage and consumption. Any water supply project that neglects this aspect will be ineffective' (UNICEF 1999).

In a recent WHO research review of diarrhoeal disease control, keeping drinking water clean in the home was identified as one of the key hygiene behaviours for preventing diarrhoea (WHO 1999). Both WHO and UNICEF describe hygiene measures aimed at maintaining clean drinking water following its collection and storage in the home (WHO 1997; UNICEF 1999). Other initiatives aimed at preventing the re-contamination of drinking water have focused on specially designed storage containers (Hammad & Dirar 1982; Empereur-Bissonnet *et al.* 1992; Roberts *et al.* 2001). In some cases the containers are designed to facilitate the household treatment of an unacceptable water supply but also stress the importance of preventing re-contamination (Mintz *et al.* 1995; Quick *et al.* 1996).

In contrast to the above viewpoint, it has been suggested that the health risk posed by re-contaminated drinking water is relatively minor compared with the risk of contaminated source water. Feachem *et al.* (1978) argued that the epidemiological significance of re-contaminated water is very different from that of source water contamination: '…such pollution [after collection] only partially negates the value of providing clean water at the tap'. They point out that pathogens transmitted by this route only affect household members, who are in any case exposed to pathogens within the household by other routes. In

contrast, source contamination permits inter-family disease. However, where a household has frequent visitors who drink the stored water, then there is a risk of inter-family disease transmission.

VanDerslice and Briscoe develop this argument, and contend that re-contaminated drinking water does not constitute a serious risk of diarrhoeal disease (VanDerslice & Briscoe 1993). They argue that household members will develop immunity to pathogens that are spread to other family members as a result of poor hygiene in the home. Since the pathogens in household stored water probably originate from the faeces of household members, further exposure to these 'internal' pathogens would not increase the risk of diarrhoea. In contrast, a contaminated water source is more likely to contain pathogens from other members of the community. They will therefore be 'external' to the family and represent a greater risk of causing a new infection. VanDerslice and Briscoe also suggest that the efficiency of pathogen transmission via stored water may be considerably less than by other household routes, such as hands or food.
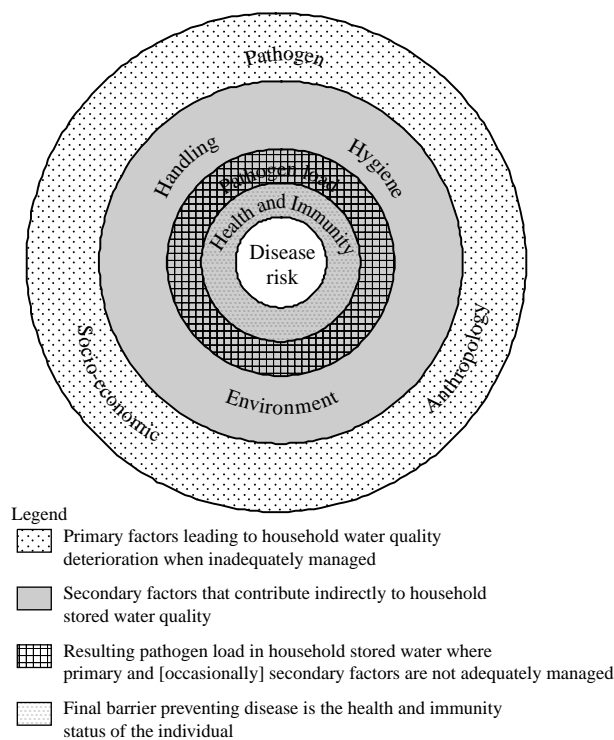
However, the strength or validity of these arguments is questionable. For example, the deterioration of drinking water quality between collection and consumption has been shown to be a common and widespread problem (Hammad & Dirar 1982; Blum *et al.* 1990; Empereur-Bissonnet *et al.* 1992; Swerdlow *et al.* 1992; Kaltenthaler *et al.* 1996; Genthe *et al.* 1997; Hoque *et al.* 1999; Roberts *et al.* 2001; Trevett *et al.* 2004). The epidemiological significance therefore may be much greater than previously believed. With respect to immunity, where an infant's immune system is still developing it is entirely possible that an infection becomes established before the immune system is fully primed. Furthermore, the widespread phenomenon of malnutrition in developing countries results in immunodeficiency, and thus more vulnerability to infection (Playfair & Bancroft 2004). As regards the differences between internal and external pathogens, the strength of this argument depends very much on the extent of interaction between family members and the external community. Considerable difficulties arise in defining what constitutes intra-familial versus inter-familial transmission. Lastly, although pathogen transmission via stored water may be less efficient than other routes such as food or hands, it is unclear why this

argument does not apply to the diarrhoeal disease risks associated with contaminated source water.

These arguments are examined in more detail in this paper, on the basis of a conceptual framework showing the processes involved in post-source water contamination. The framework is used as a conceptual tool to assess the health risk of consuming re-contaminated drinking water.

TOWARDS A CONCEPTUAL FRAMEWORK

The transmission of infectious disease is a complex process that cannot be predicted to a high degree of accuracy. There are many determinants of ill health, and a conceptual framework helps us to understand which of these are the most important in disease transmission. We have developed such a framework that is specific to the context of drinking water that has become contaminated between collection and consumption (Figure 1). At the centre of the framework

Legend

Primary factors leading to household water quality deterioration when inadequately managed

Secondary factors that contribute indirectly to household stored water quality

Resulting pathogen load in household stored water where primary and [occasionally] secondary factors are not adequately managed

Final barrier preventing disease is the health and immunity status of the individual

Figure 1 | A conceptual framework showing the primary and secondary factors that determine the potential pathogen load in household stored drinking water, and the final barrier preventing disease.

is the 'disease risk' that results from consuming re-contaminated drinking water. The final barrier preventing disease is the 'health and immunity' status of the individual. As observed by Eisenberg *et al.* (2001), the existing state of health largely determines the ability of the body's immune system to fight off infection. Secondary immunodeficiency, caused for example by malnutrition, HIV, helminthiasis and other infections, significantly impairs the individual's response to waterborne pathogens. Furthermore, in the case of most waterborne pathogens, acquired immunity is partial and temporary.

The 'pathogen load' in household stored drinking water refers to the concentration and category of pathogens present in the water. If stored water contains pathogens in sufficient numbers to constitute an infective dose, and the pathogen is 'new' to the immune system, then the individual will suffer clinical disease (E. Ingham, School of Biochemistry and Molecular Biology, University of Leeds, personal communication, 11 October 2001). The 'pathogen load' is determined by primary factors – 'handling', 'hygiene' and 'environment' – and secondary factors – 'pathogen', 'anthropology' and 'socio-economic'. The significance and definition of each factor with respect to the conceptual framework is explained as follows.

Primary factors

'Handling' refers to household water management, and specifically to the way in which water is collected, transported, stored and used. Inevitably the practices surrounding handling will vary between households and communities. Water handling practices determine the extent to which water becomes contaminated between collection and use. In our research in Honduras we observed an immediate deterioration in water quality as collection containers were filled, presumably caused by inadequate washing of the container, or hand contact; see 'hygiene' below (Trevett 2003). We also found that different serving methods had a significant effect on water quality. The introduction of a special container to prevent water contact with a serving utensil or hand has been widely advocated (Mintz *et al.* 1995; Quick *et al.* 1996; Roberts *et al.* 2001). Several other handling factors are potentially implicated in post-supply water quality deterioration. These

include the use of separate containers for collection and storage (Lindskog & Lindskog 1988), the material from which the storage container is made (Mertens *et al.* 1990; Ahmed *et al.* 1998), the practice of filtering collected water with a cloth prior to storage (Janin 2000; Trevett 2003), and keeping storage containers covered (Empereur-Bissonnet *et al.* 1992; Jagals *et al.* 1997).

'Hygiene' in this context refers exclusively to hand washing. There is strong evidence to suggest that hand–water contact is a principal cause of the re-contamination of drinking water. It is arguable that hand–water contact is unavoidable in situations where water must be collected, transported and stored. Consequently, if hands are unclean there is a high risk that drinking water will become contaminated as a result of contact made during normal household water management. In our Honduran research, hand contact with drinking water was regularly observed at all stages of the collection to consumption process (Trevett 2003). Furthermore, a high proportion of children were observed to collect and serve water, and it is reasonable to assume that children will take less care to avoid hand–water contact. Several other studies have reported similar findings linking hand contact to water quality deterioration (Feachem *et al.* 1978; Blum *et al.* 1990; Pinfold 1990a; Hoque *et al.* 1995; Roberts *et al.* 2001). We asked women before/after which activities they used soap to wash their hands in our Honduran research (Trevett 2003). Around 70% stated they washed their hands with soap before food preparation, 42% before eating and 36% after defecation. No mention was made of washing hands with soap before carrying out any drinking water practice.

'Environment' means the sanitary quality of the house-hold and community environment. Given that infectious disease is largely transmitted through human and, to a lesser extent, animal faeces, then increasing levels of exposure to faeces are likely to be associated with an increased risk of disease. Therefore, open defecation (human), the presence of animal faeces in the home or yard, open sewers (urban areas), the practice of reusing excreta in some societies, population density and climate, all affect the risk of an individual's exposure to pathogens. In the rural communities included in our study in Honduras, around half of the households had access to a latrine, faeces from domestic animals and livestock were widely observed in and around the home, and occasionally children's faeces were seen on the floor of the sleeping area (Trevett 2003).

Secondary factors

'Socio-economic' factors include the level of education and, more specifically, knowledge of good hygiene practice. To some extent making use of such knowledge is dependent on household income. In situations of *extreme* poverty the household's ability to improve or maintain the sanitary environment of the home will be limited.

The level of formal education, especially of women and in rural areas, is typically very low in developing countries. In the villages included in our Honduran research, nearly half of the female heads of household had not received any formal schooling, and only a quarter had completed primary education (Trevett 2003). The women were also asked about using soap for hand washing. In all but one household (36 households surveyed) the women knew the price of soap and 61% commented on how long the soap lasted. However, the soap was stated as being for both dishwashing and hand washing. Furthermore, although soap was regularly seen during household visits, hand washing with soap was not observed. If in fact soap is rarely used for hand washing, it could be because it is thought too expensive. Such a finding was reported by Hoque *et al.* (1995) in their study from Bangladesh.

The 'Anthropology' factor focuses on the cultural values and norms held by different societies, of which there may be several distinct groups in a country. The degree of social interaction within families, and between neighbours and strangers is an important factor in the epidemiology of infection. For example, to what extent are communities formed of nuclear versus extended families? Are farming activities based on cooperative systems? Is there a practice of reusing excreta in agriculture? Are there migratory working practices? How extensive is the external (to the community) interaction with schools, clinics, markets and other social congregations? The anthropological characteristics of communities vary greatly according to values and location of the community. For example, an isolated mountain village may have less opportunity for social interaction than a peri-urban community. However, cultural values and relative iso-

lation will influence the introduction of 'new' pathogens to the community, and disease transmission between households.

In the study villages in Honduras, we observed that communities consisted of several extended families, often living as neighbours. It was common for family members to look after infants and children, and provide them with meals and water to drink. We also observed non-family members offered drinking water, and occasionally individuals known to the household might serve themselves water. This represents a potential transmission route of pathogens from and to stored drinking water. Pinfold (1990b) reported a high degree of social interaction between households in a study of household water quality in rural communities in Thailand.

The 'Pathogen' type or category is important in estimating the health risk of re-contaminated drinking water. Transmission to a new host is partly determined by the individual qualities of different pathogens or strains. Several pathogen characteristics are of particular relevance to the present paper, including persistence, virulence, infective dose and growth rate. It is important to bear in mind that these characteristics vary widely between pathogens and in some cases between pathogen strains.

All waterborne pathogens exhibit persistence, the ability to survive outside the human host, to some extent. The persistence of bacteria such as *Shigella* spp. and *Vibrio cholerae* is relatively short (up to one week), whereas the protozoa *Giardia intestinalis* may survive for up to one month at 20°C. Several factors affect persistence in water, though temperature is the most important. The rate of pathogen decay is usually accelerated by increasing water temperature, and may be brought about by the action of ultraviolet radiation from sunlight on the water surface (WHO 1993). Nasser and Oman (1999) observed higher inactivation rates of poliovirus and hepatitis A virus at higher temperatures in natural water sources. Pinfold (1990b) reports that bacterial survival on fingertips increases with high humidity, suggesting that persistence may vary according to season. Pinfold (1990a) also comments on the variation in survival times of different bacteria on human skin. Assuming that hands are involved in the re-contamination of water, this implies that seasonal variation and those pathogens more able to survive on skin are factors affecting disease risk.

Another important characteristic of a pathogen is its virulence, defined here as 'the ability of any infective organism to cause disease' (Youngson 1992). Thus, exposure of a non-immune individual to a pathogen of high virulence is likely to result in disease. Where the immune system is compromised, for example as a consequence of being malnourished, or underdeveloped, as in the case of an infant, the individual is more susceptible to disease (Murray *et al.* 1994).

The infective dose refers to the number of organisms needed to cause infection. Attempts have been made to determine the number of pathogens that constitute an infective dose. For example, less than 200 *Shigella* spp. are required to cause shigellosis, whereas around 10^8 *Vibrio cholerae* organisms need to be ingested to cause cholera (Murray *et al.* 1994). However, much of the information on infective dose has been gathered from experimental studies on healthy adult volunteers, and may have only limited relevance to natural transmission in the case of malnourished infants (Feachem *et al.* 1983). Most importantly, the infective dose will be higher or lower according to an individual's immunity, which is affected by age, sex, health and living conditions (WHO 1993).

Most pathogens are not thought to be capable of multiplication in water. However, in conditions where there are high levels of biodegradable carbon and warm temperatures, opportunistic pathogens such as *Pseudomonas aeruginosa* and *Aeromonas* have been found to grow in water distribution systems (WHO 1993). Biofilms in water pipes are known to allow the proliferation of *Legionella* and *Mycobacterium avium* (Hunter *et al.* 2001). The growth and survival of indicator microorganisms in household storage containers was reported in a study carried out in two rural communities of South Africa (Momba & Kaleni 2002). It has also been speculated that the porous surface of clay containers used for household water storage may be favourable to bacterial growth (Ahmed *et al.* 1998; Janin 2000; Trevett 2003).

In summary, primary factors largely determine the pathogen load in household stored water, though secondary factors may be described as contributory. Primary factors may also be viewed as representing target areas for the development of practical intervention strategies. It is evident that where primary factors are adequately mana-

ged, then secondary factors will be of relatively minor concern.

PURPOSE OF THE CONCEPTUAL FRAMEWORK

The conceptual framework provides a starting point to develop a series of hypotheses that relate to the risk or actual occurrence of disease transmission through consumption of re-contaminated water. It is not the purpose of this paper to produce an exhaustive list of hypotheses but instead provide a few examples that can either be examined in the light of existing literature, or indicate areas for further research (Table 1). Clearly, some of these hypotheses would be impractical to research because of the complex interlinking of disease-causing factors. Nevertheless, there are studies that have considered similar hypotheses and are relevant to the issue of disease risk from consuming re-contaminated drinking water. Most of the evidence considered below relates to the primary factors, though some examples of studies relevant to the hypotheses indicative of secondary factors are also included.

EVIDENCE OF DISEASE RISK

Handling

Although it is difficult to separate some of the studies that address handling factors from others that consider hygiene, it is useful to make this distinction to better understand the relative importance of each factor. Several studies have demonstrated that water quality deterioration can be significantly reduced using specially designed storage containers (Hammad & Dirar 1982; Empereur-Bissonnet *et al.* 1992; Roberts *et al.* 2001). Others have investigated how special containers may help to prevent re-contamination in conjunction with point-of-use disinfection (Mintz *et al.* 1995; Quick *et al.* 1996, 1999). However, only one published study has been found that reports on the specific question surrounding the health impact of consuming drinking water that was safe at the point of supply but deteriorated in quality during its collection, transportation and storage in the home. Roberts *et al.* (2001) carried out an intervention study in a Malawi refugee camp using an improved container. A 31% decrease in diarrhoeal disease was observed in children under 5 years of age where households used the special container. In another intervention study, Deb *et al.* (1986) introduced a 'sorai' to store drinking water (narrow-necked clay container) in urban slums in India. They reported that the cholera carrier rate in the intervention group was 4.4% compared with 17.3% in the control group.

Several studies have reported on the links between disease incidence and the type of water storage container, or the method used to remove stored drinking water. For example, in a study carried out in the Eastern Province of Saudi Arabia, Qadri *et al.* (1992) concluded that diarrhoeal morbidity in children under 5 years of age was significantly associated with the type of water storage container, though

Table 1 | Examples of hypotheses relating to disease risk from the consumption of re-contaminated drinking water according to conceptual framework factors

Primary/secondary factor	Hypothesis
Handling	Improved storage containers maintain good water quality and lead to reduced disease incidence Minimising handling can be linked to lower disease incidence
Hygiene	Hand contact with drinking water can be linked to disease transmission Improving hygiene/hand washing behaviour leads to reduced water pollution in the home
Environment	Improving sanitary quality of the environment leads to better water quality Household's own excreta is implicated in disease incidence
Anthropology	Communities exhibiting a high degree of social interaction experience greater incidence of disease than more 'closed' cultures
Socio-economic	Stored water quality is worse in the poorest households/communities

no explanation of this finding is given. Knight *et al.* (1992) reported a non-significant association between diarrhoea and the type of storage container (narrow versus wide necked) in their study of diarrhoea transmission risk factors in rural Malaysia. In a study carried out in a peri-urban community in Peru, Yeager *et al.* (1991) concluded that children were twice as likely to suffer a high incidence of diarrhoea in households where water was stored in containers without a tap. Singh *et al.* (1995) report that storing water in wide-mouthed containers and using a glass or mug to draw water were important risk factors for cholera cases.

In a study of shigellosis transmission in Zambia, Tuttle *et al.* (1995) found that illness was independently associated with dipping a cup into the household drinking water container. Islam *et al.* (2001) found that *S. dysenteriae* type 1 was viable (but non-culturable) on cloth, plastic and glass 5 days after inoculation, and suggest that, in developing countries such as Bangladesh where poor hygiene is practised, drinking glasses are important vectors of shigellosis. Patel & Isaäcson (1989) compared the survival of El Tor and Classical biotypes of *V. cholerae* in water storage containers commonly used in South Africa and found that seepage water from clay pots contained cholera bacilli. The authors suggest that cholera pathogens could easily be transmitted to hands and food through handling the clay containers. Mahmud *et al.* (2001) report that, among infants in rural communities in Egypt, water storage in 'mud containers' was associated with persistent diarrhoea.

Other studies report that diarrhoeal disease is associated with not covering the water storage container. For example, in a case-control study in a poor urban settlement in South Africa (cases of diarrhoea reported at *Medicines du Monde* clinic), it was observed that 74% of case households stored water in open containers as opposed to only 54% in control households (Jagals *et al.* 1997). Furthermore, although water supplied was of similar quality (geometric mean <2 FC (Faecal Coliforms) $100 \, ml^{-1}$), stored water in case households was found to be highly contaminated with a geometric mean of 1,207 FC $100 \, ml^{-1}$, versus 6 FC $100 \, ml^{-1}$ in control households. Mirza *et al.* (1997) report that uncovered water containers were among the significant factors influencing recovery from prolonged diarrhoeal disease in a study carried out in an urban slum area in Kenya.

A few studies have reported the presence of pathogens in household stored water but not in supplied water or in significantly lower numbers. Examples include *V. cholerae* (Gunn *et al.* 1981; Deb *et al.* 1982), *Ascaris* and *Strongyloides* (Khairy *et al.* 1982), and *Giardia* spp. (Genthe *et al.* 1997).

Hygiene

Clearly, there are many opportunities for hand–water contact to occur during the handling of household drinking water. Our own observations in Honduras found faecal contamination on 44% of the fingertips of women tested during normal household activities (Trevett 2003). Other more in-depth studies have reported similar findings (Pinfold 1990a; Hoque *et al.* 1995; Kaltenthaler *et al.* 1991, 1996), and pathogenic Enterotoxigenic *Escherichia coli* (ETEC) were recovered from mothers' and children's hands in a study carried out in Thailand (Echeverria *et al.* 1987). Such studies strongly support the current interest in the promotion of hand washing at critical times.

If hands are frequently contaminated with faecal material, then it is quite feasible that pathogens could be easily transferred to stored water. However, evidence linking hand contamination of stored drinking water with disease transmission is limited. In a case-control study of cholera transmission in an urban suburb in Peru, drinking water from household containers into which hands had been introduced was strongly associated with illness (Swerdlow *et al.* 1992). Comparable results were reported in a study of cholera among refugees in Malawi, and additionally *V. cholerae* 01 was isolated in household water storage containers. It was even reported that refugees acknowledged that they rinsed their hands in household stored drinking water (Swerdlow *et al.* 1997). In contrast, 51% of respondents to a household survey in peri-urban communities in Bolivia stated that hands occasionally made contact with water when serving but this was not found to be associated with diarrhoeal illness (Quick *et al.* 1999). A similar conclusion was reached in a case-control study of cholera patients in the City of Fort-Dauphin, Madagascar (Reller *et al.* 2001). Around 90% of households served stored water using a cup or ladle, which may have introduced contamination thus confounding the effect of hand–water contact.

Environment

The overall sanitary condition of both the domestic environment and the community as a whole can be expected to have an impact on household stored water quality. Where systems of safe excreta disposal are absent, the transfer of faecal material may be widespread. Kaltenthaler *et al.* (1996) report that around 30% of both washed and unwashed plates were contaminated with faecal coliforms in a study carried out in rural Botswana. Furthermore, 52% of wet dishcloths, 23% of dry dishcloths and 40% of infant feeding bottles also exhibited faecal contamination. Children from families with poor hygiene conditions suffered more diarrhoea than those with good levels of hygiene.

VanDerslice *et al.* (1994) examined the interactive effects of drinking water quality, sanitation and breast-feeding in urban areas of the Philippines. It was reported that diarrhoea risk nearly doubled for fully breast-fed infants when only small quantities of contaminated water supplemented breast milk. A related study concluded that good water quality had the greatest positive health effect when sanitary conditions were also good. However, improving water quality did not reduce diarrhoeal disease where sanitation remained poor (VanDerslice & Briscoe 1995).

Reducing the overall level of excreta in the environment has also been shown to benefit even households without latrines. Child diarrhoeal morbidity was compared in two similar rural communities in Zimbabwe (Root 2001). In community A 62% of households had latrines; in community B there was no sanitation. Diarrhoeal morbidity was 68% lower in community A than community B. Furthermore, children from households without a latrine in community A suffered less diarrhoea than those in community B. Intra-familial transmission of diarrhoea in community A was indicated by significantly higher number of diarrhoea episodes in households without latrines. Roberts *et al.* (2001) also found evidence of intra-familial diarrhoeal disease. It was observed that in households where faeces were seen on the floor of the latrine, children under five years of age had a greater risk of suffering diarrhoea than in homes with clean latrines.

Based on hygiene-related studies in peri-urban areas of Peru, Lanata *et al.* (1998) speculate on the sources of faecal contamination that might affect children under two years. They concluded that, although children's own faeces are unlikely to be a threat to themselves, the faeces of infants or young siblings, particularly when they have diarrhoea, represent '…the greatest threat for a young child'. This is because infected infants, or those with subclinical infections, excrete large numbers of enteropathogens in or around the home, thus representing a direct threat. In contrast, older children or adults are unlikely to defecate in the vicinity of an infant, though their faeces may be important where they lead to contamination of drinking water.

Sanitary conditions in the household are also affected by keeping animals in the home. Quick *et al.* (1999) report that *Campylobacter* spp. was isolated in stool samples from 9% of intervention households (provided with special water storage container), and 43% of control households. It was observed that a large proportion of families kept poultry, which can carry *Campylobacter* spp. Water is a recognised transmission route of infection, and the introduction of a special storage container appears to have led to a marked reduction in infection. In Honduras we observed that 81% of households kept chickens in or around the home, and were often seen on tables where water storage containers were placed (Trevett 2003).

Anthropology

There are an infinite number of factors that could lead to disease transmission through household water. Cultural norms determine anthropological factors and these may vary between households and communities as well as the more obvious differences between societies. The following study examples serve to illustrate the links between anthropological factors and the potential for disease transmission via household stored water.

Swerdlow *et al.* (1992) report that going to a *fiesta* (social event) was significantly associated with cholera in a study of epidemic cholera in Peru. Food and drink is likely to have come from a variety of sources and been prepared by a number of different people. It is suggested that newly infected persons could then transmit cholera to their own household through hand contact with stored drinking water.

In a hand-washing study in Zimbabwe, Kaltenthaler *et al.* (1991) found higher faecal indicator bacteria counts on

the hands of people recently involved in farming than those engaged in other activities. Higher bacterial counts were also recorded on the hands of solid waste collection workers than for a control group of workers in a study carried out in urban Egypt (El-Sebaie 1994). The implication is that, where poor hygiene is practised, there is a risk pathogens could be introduced into stored drinking water. In these study examples any pathogens would probably be external to the family.

Socio-economic

Many studies have examined the relationship between socio-economic factors and diarrhoeal disease. For example, Yeager *et al.* (1991) developed a socio-economic status indicator (SES) in order to compare diarrhoea incidence in a peri-urban community in Peru. The SES indicator was based on four variables: income, ownership of five functioning electrical household appliances, community participation, and house construction. Although no clear association was found between low SES children and higher diarrhoea incidence, the transmission factors with which SES is associated were significantly related to diarrhoea. In contrast a study carried out in two Bangladesh villages, reported that the duration of diarrhoea in children was significantly longer for children in low-income households (Becker *et al.* 1986).

Manun'Ebo *et al.* (1994) studied the influence of demographic, socio-economic and environmental factors on childhood diarrhoea in rural Zaire. Parental education and household size were associated with diarrhoeal disease risk in children aged 3–35 months. Mahmud *et al.* (2001) report that socio-demographic factors (infant and mother age, infant sex, illiteracy) were important risk factors in developing persistent diarrhoea in rural Egyptian communities. Newman *et al.* (1999) found that low-birth-weight children and those living in densely crowded urban slums in Brazil were important factors in the incidence of *Cryptosporidium* infection. Wolff *et al.* (2001) concluded that improved housing (houses with fired mud bricks, tiled roofing, concrete foundation, and a pit latrine) significantly reduced the disease burden in rural communities in Malawi.

DISCUSSION

How might the 'two opposing viewpoints' be reconciled in the light of the above evidence? One explanation is simply that the case-specific routes that lead to diarrhoeal disease are extremely difficult to identify. Furthermore, there are numerous and distinct pathogen types involved in diarrhoeal disease that can infect a new host via multiple pathways. Therefore, it is not surprising that apparently contradictory data are reported, and is the reason why a wide range of reduction in diarrhoeal morbidity is attributed to water quality improvements. Comparisons between studies are often difficult because of the different methodological approaches taken, as well as widely varying study contexts.

Fitting the descriptive information from the VanDerslice and Briscoe study (1993) to the conceptual framework proposed in this paper leads to a prediction of low disease risk. This outcome is based specifically on the description of socio-economic, environment and handling factors. For example, it is reported that the education level of the study population was high, salaried workers head 70% of households, and almost all households enjoyed access to improved water supply. Taken together this suggests household socio-economic conditions were quite good. The sanitation factor also indicates relatively low 'environment' risk, with more than 75% of households having a flush or pour-flush toilet. As for 'handling', with the exception of a small proportion of clay jars (estimated at 17%), water was usually poured from the storage container. Therefore, it can be reasoned that the pathogen load in household stored water would be relatively low. Additionally, the 'health and immunity' barrier is likely to reduce the severity of disease given the relatively good socio-economic status. Therefore, no significant association would be expected between diarrhoeal disease and re-contaminated drinking water. However, this conclusion would appear to contradict the association between source water quality and diarrhoea reported by VanDerslice and Briscoe (1993).

Several reasons might be put forward to explain this discrepancy. For example, a diarrhoeal disease model is used to predict the risk of diarrhoea, which is based on estimated levels of in-house contamination and the daily dose of faecal coliforms. A question of confidence arises in using such estimates. Furthermore, although these estimates

may be within an acceptable margin of error, there is a possibility that critical factors may be missed. For example, Moe *et al.* (1991) reported that children had significantly higher rates of diarrhoea when drinking water had greater than 1,000 *E. coli* per 100 ml but moderately contaminated water had little effect on illness rates. They suggest that there could be a threshold effect where drinking water quality becomes important as a major source of diarrhoeal pathogens only when it is grossly contaminated.

Clearly, there is a need for further research to deepen our understanding of diarrhoeal disease transmission. Given that a large proportion of communities in developing countries depend on water systems that require the users to collect and store drinking water, it is important that we are able to judge the significance of any associated health risks. One approach that this research might take is to develop a disease risk index based on the factors in the conceptual framework and their inter-relationships. This index could then be tested in case-control or intervention type studies. In this way it would be possible to learn more about the health risks from consuming re-contaminated water, and identify potential interventions for minimising disease transmission by this pathway.

CONCLUSION

We would argue that there is a considerable body of evidence to indicate that drinking water that has become contaminated between the point of supply and point of collection represents a significant health risk to infants in particular. While the arguments put forward by VanDerslice and Briscoe (1993) may be valid under certain conditions, there are several scenarios imaginable where there is a strong likelihood that disease transmission will be the outcome of in-house water pollution. Infants are vulnerable to low doses of pathogens during the developmental stage of the immune system, and where they are malnourished the infective dose is effectively lowered. Although household drinking water may be a less efficient mechanism than either food or hands, this is not to say that it is without risk. It would be imprudent not to safeguard drinking water between collection and consumption. The use of re-contaminated water in food preparation, where pathogen multiplication can occur, is a further reason to advocate

safe water handling and storage. Finally, household stored water might be one route by which new pathogens are introduced to the household. Social interaction by children and adults alike will lead to the transmission of pathogens via water, food and physical contact.

Although some of the evidence presented in this paper is by necessity circumstantial, this reflects the complexity of the interaction of the distinct factors involved in faecal–oral disease transmission. There is a growing interest in providing safe drinking water up to the point of consumption, and it is probable that new evidence will emerge on the question of the relative health risk from consuming re-contaminated drinking water. For the time being it is our conviction that there is already sufficient evidence of the health risk, and we recommend that attention be given to developing practical strategies to ensure safe drinking water is provided at the point of consumption. A forthcoming paper will consider the strategies that should be adopted by agencies involved in the water sector in developing countries.

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