Health risk assessment of non-potable domestic water supplies in the Netherlands

Frank Oesterholt, Gerard Martijnse, Gertjan Medema and Dick van der Kooij

ABSTRACT

Dual water supply systems were installed in several newly built housing estates in the Netherlands in the late1990s. These residential homes were provided with both drinking water and separately with so-called household water for toilet flushing, laundry and the garden tap. Household water was produced by limited treatment from a variety of sources and had a lower quality than drinking water. No legislation for (the quality of) this type of water was present at the time and the Dutch government appointed six of these estates as pilot projects. Four pilot projects were intensively monitored for toxicological and microbiological safety as well as microbiological stability during a period of almost 16 months.

Specific incidents such as cross connections between drinking water and household water and observations of viruses and pathogenic protozoa in treated water demonstrated that some of these systems were microbiologically unsafe. Furthermore certain household waters had a relatively high biofilm formation potential leading to growth of *Legionella* sp. and *Aeromonas* and complaints from customers about the smell and colour of the household water. In nearly all cases concentrations of heavy metals and organic pollutants were below drinking water standards, hence the toxicological risk caused by chemical substances was not significant.

Based on the results of this study the Dutch government decided to discourage the production and distribution of household water on a large scale. At present all projects owned by water companies in the Netherlands have been terminated by replacing household water with drinking water.

Key words | drinking water, dual water supply, grey water, household water, microbiological safety, microbiological stability

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INTRODUCTION

Dual water supply systems in housing estates were developed in the Netherlands in the late 1990s to further enhance the sustainability of the water supply in general. For this purpose in several newly built housing estates a drinking water supply system together with a separate water supply for non-potable use were installed. The secondary water is called household water which is defined as non-potable water centrally produced from surface water, groundwater or an alternative source such as rainwater and intended for 'no direct contact' use for example toilet flushing, washing of clothes, garden watering and car washing.

The Dutch government considered the established dual water supply systems to be experimental on a practical scale. In 1999 the Minister of Housing Spatial Planning and the Environment (VROM) officially appointed six new housing estates with dual water supply as pilot projects. Monitoring of these pilot projects during a period of sixteen months should yield all the necessary information on the effects of the use of household water on public health and

doi: 10.2166/aqua.2007.043

the environment, as well as on aspects concerning public information and appreciation. Economic aspects of household water were not part of this study.

This paper reports the observations of the monitoring study of these pilot projects during the period May 2001 to August 2002 focussing on the potential health risks of these systems. The results of this study were to be used by the Dutch government to define their policy on the distribution and use of household water.

Dual distribution systems for urban areas have been realised worldwide, especially as a water saving instrument in places with local water shortages (Okun 1997). Mostly small scale domestic water reuse systems using grey water or rainwater are reported (Dixon *et al.* 1999*a*; Lazarova *et al.* 2003; Birks *et al.* 2004) and sometimes dual system technology is promoted for reclamation of wastewater and reuse in communities (Okun 2000; Lu & Leung 2003). In recent years more attention has been given to health risks associated with the reuse of grey water or reclaimed wastewater in households (Dixon *et al.* 1999*b*; Albrechtsen 2002; Ottoson & Stenström 2003). In general these references express a delicate balance between public health and reuse of rainwater or grey water in households.

HEALTH RISK STUDIES AND PROVISIONAL GUIDELINES

Incidental exposure to pathogenic micro-organisms is considered as the major potential health concern of household water use (Versteegh *et al.* 1997). The toxicological risk caused by chemical substances was considered to be low due to the very low and non chronic exposure to household water. Therefore the preliminary standards for chemical substances proposed were mainly based on environmental or ethical grounds. Furthermore a qualitative analysis of the microbiological risks showed that the major risk is the ingestion of household water from the garden tap intended for watering the garden or car washing.

The Dutch Water Supply Decree (VROM 2001)[1] demands surface water suppliers to demonstrate that the infection risk caused by the presence of pathogenic micro-organisms in drinking water is less than one infection per 10,000 persons per year (10^{-4} infection risk). In households that are connected to a dual water supply household water has replaced drinking water for certain applications. In these cases it is reasonable that the 10^{-4} infection risk is used as a reference to the combined use of household water and drinking water within the household. Theoretically, household water complies with the 10^{-4} infection risk at a (much) lower quality than drinking water.

The exposure to micro-organisms in household water through aerosols formed during (i) toilet flushing, (ii) watering the garden, (iii) use of high-pressure water hose and (iv) drying of clothes in a tumble drier as well as (v) through direct contact with wet clothes from a washing machine has been evaluated by Medema *et al.* (1998). By combining these exposure-data and data on the microbiological quality of household water, point estimates can be made of the infection risk caused by exposure to household water in pilot systems.

DESIGN OF THE STUDY

The basis of the study was a water quality monitoring program. Household water at four sites (see Table 1) was characterised from source to tap by analysis of chemical and microbiological parameters on a periodic basis. The program focussed on health aspects concerning toxicological safety, microbiological safety and microbiological stability, as presented in this paper, as well as environmental effects and public information and appreciation (e.g. aesthetic aspects).

The project at site III is a rain water supply system not owned by a water company but by an association of house-owners. The other projects (sites I, II and IV) were owned by water companies.

TOXICOLOGICAL SAFETY

Chemical analysis included heavy metals, pesticides, polycyclic aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCB) and benzene following standard analytical

[1]Water Supply Decree is based on European Legislation, "Water intended for human consumption", 1998

Table 1 | Specifications of four (out of six) pilot projects with a dual water supply system, appointed by the Dutch government

Site nr.	Scale	Water source(s)	Treatment processes	Intended application	Supply period
I	max. 1,200 houses (in pilot); 7,000 houses (final situation)	Surface water from a canal (Beatrix canal)	$KMnO_4$-dosage Membrane filtration (UF) Granular activated carbon filtration (from Nov. 2001)	Laundry toilet flushing	April 2001 – October 2002
II	400 houses (in pilot); 30,000 houses (final situation)	Surface water from a canal connected to the river Rhine (Lek canal)	Coarse filter CFS[1] pH-correction Rapid sand filtration	Laundry toilet flushing garden tap	1999 – December 2001
III	240 houses	Rain water	Coarse rain water filter	Toilet flushing	1998 – present day
IV	162 houses	Ground water (seepage water) + surface water from a small ditch after soil passage	2-Step sand filtration UV-disinfection	Laundry toilet flushing garden tap	May 2000 – October 2002

[1]CFS = Coagulation/flocculation/sedimentation.

procedures. These parameters were analysed in the source water, in the household water directly after treatment and at taps in a few selected houses. The results were evaluated by comparison to the preliminary standards for household water (Versteegh *et al.* 1997) and the Dutch drinking water standards (VROM 2001).

MICROBIOLOGICAL SAFETY

Microbiological safety was evaluated by performing a quantitative risk assessment. The required input for this risk assessment was obtained by analyzing the source water for the following human pathogens: *Cryptosporidium*, *Giardia*, rotaviruses, noroviruses, enteroviruses and *Campylobacter*. In addition the source water as well as the household water after treatment was analyzed for faecal indicator organisms. *Cryptosporidium/Giardia* were analyzed using the EPA 1623 method (EPA). Enteroviruses were concentrated as described in Van Olphen *et al.* (1984) and analyzed on Buffalo-Green Monkey cells. Rotaviruses and noroviruses were concentrated using the same filtation/elution method and purified and assayed according to Lodder *et al.* (1999) using RT-PCR in serial dilutions resulting in a number of RNA containing particles per litre (RCP/litre).

The point assessment of the microbiological risk was performed in six steps:

(i) Survey of pathogenic micro-organisms and indicator organisms in the source water.
(ii) Determination of the available decimal elimination capacity (DEC = log removal) of the treatment processes (using indicator organisms).
(iii) Assessment of the mean concentration of pathogenic micro-organisms in household water.

$$C_{hhw} = 10^{-DEC*} C_{source} \quad \text{in [n/l]} \tag{1}$$

Where C_{hhw} is the calculated concentration of a pathogenic micro-organism per litre of household water, DEC [−] is the mean elimination capacity (log units) of the treatment for this micro-organism determined with indicator organisms and C_{source} is the mean of the measured concentrations per litre of the micro-organism in the source water.

(iv) Combination of the concentrations in household water (C_{hhw}) with data from Medema *et al.* (1998) to calculate the total exposure (E_{total}) to micro-organisms in household water for different applications.

$$E_{total} = F_{total} * C_{hhw} \quad \text{in [n/year]} \tag{2}$$

where E_{total} = the total annual exposure of a person to a certain pathogenic micro-organism through contact with household water, C_{hhw} is the calculated concentration of a pathogenic micro-organism per litre

household water and F_{total} is calculated by:

$$F_{total} = F_{toilet\ flushing} + F_{high\ pressure\ hose} + F_{garden\ watering} + F_{washing\ of\ clothes} + F_{direct\ contact\ to\ wash} \quad \text{in [l/year]} \tag{3}$$

where F_{total} is the equivalent of the total amount of household water to which a person is exposed annually, $F_{toiletflushing}$ is the equivalent of the fraction household water to which a person is exposed annually through toilet flushing, etc.

(v) Assessment of the infection risk from the total exposure (E_{total}) using available dose-response relationships for different pathogenic micro-organisms, using:

$$P_{inf} = f\{E_{total}\} \tag{4}$$

where P_{inf} is the infection risk for a pathogenic micro-organism, E_{total} = the total annual exposure of a person to a certain pathogenic micro-organism by direct contact with household water and f(x) is a dose-response relationship for the specific micro-organism.

- enteroviruses; $f(x) = 1 - EXP(-0.014472 * x)$ (Coxsackie, Haas *et al.* 1999)
- rotaviruses; $f(x) = 1 - (1 + x/0.42)^{-0.26}$ (Teunis *et al.* 1994)
- noroviruses; $f(x) = x/100$ (see note)
- *Cryptosporidium;* $f(x) = 1 - EXP(-0.004202 * x)$ (Teunis *et al.* 1994)
- *Giardia;* $f(x) = 1 - EXP(-0.0199 * x)$ (Teunis *et al.* 1994)
- *Campylobacter*; $f(x) = 1 - (1 + x/7.59)^{-0.145}$ (Medema *et al.* 1996)

Note: for noroviruses the assumption is made that the relation between RCP and infectious virus is 100:1 and that every exposure to an infectious virus leads to an infection.

(vi) Comparison of total infection risk for all micro-organisms to 10^{-4} infection risk.

MICROBIOLOGICAL STABILITY

The microbial-growth promoting properties of household water was studied with AOC analysis, the biofilm monitor and by examining segments taken from pipes in selected houses. The AOC concentration was determined by measuring the growth of two selected pure bacterial cultures in samples of the water contained in thoroughly cleaned Erlenmeyer flasks (Van der Kooij 1992). The biofilm formation rate (BFR, pg ATP/cm^2.d) of the water was determined on glass cylinders exposed to water in a glass column at a flow rate of 0.2 m/s. Total exposure time was 150 days. Glass rings were periodically collected and biofilm concentrations were determined with ATP analysis. Also concentrations of iron and manganese were determined (Van der Kooij *et al.* 1995). Biofilm concentrations on the pipe surface were determined by collecting biomass from the inner surface of the pipe segments using sterile cotton swabs. Subsequently, ATP analysis was conducted to determine the amount of biomass.

RESULTS AND DISCUSSION

Toxicological safety

The concentrations of organic pollutants and heavy metals in household water at all four locations were low and complied to drinking water standards in most cases. Consequently, no chemical toxicity effects from household water are expected. Table 2 gives an overview of the few situations in which the mean concentrations exceeded the standards for drinking water and/or the preliminary standards for household water. Since the daily ingestion of household water is very low, these situations do not represent a toxicological significance.

Microbiological safety

At all four locations the source for production of household water was contaminated with pathogens of faecal origin. The household water at sites I and IV was considered microbiologically safe due to ultrafiltration at the first site and the combination of soil passage, sandfiltration and UV-disinfection at the second site. The safety margins at site I were relatively high (5 logarithmic units for viruses and 3 units for other pathogens), however only a single barrier is present and the integrity of the ultrafiltration membranes needs continuous monitoring.

Table 2 | Non-compliance of chemical parameters in household water to drinking water standards and preliminary household water standards

		Mean concentration (μg/l)			
Site	**Parameter**	**Source water**	**Household water**	**Preliminary standards for household water (RIVM 1997)**	**Drinking water standards (VROM 2001)**
I	Nickel	19–43	12–37	9 (env.)*	20 (tox.)**
	Selenium	<1–1.5	1–12	10 (env.)*	10 (tox.)**
	Cadmium	2.2–7.8	<0.2–0.4	0.05 (env.)*	5 (tox.)**
IV	BAM	0.43–0.47	0.37–0.41	5[a] (eth.)#	0.1 (tox.)**

BAM = 2,6 dichlorobenzamid, metabolite of dichlobenil (toxicologically irrelevant for humans).
[a]total concentration of pesticides.
*env. = standard based on environmental grounds.
#eth. = standard based on ethical grounds.
** tox. = standard based on toxicological grounds.

The household water at site IV was classified as unsafe because faecal indicator organisms were present with high variations in concentration. *Cryptosporidium* oocysts and *Giardia* cysts were found in the rain water tank as well as in the household water system because of the absence of a significant barrier. At site IV household water was only used for toilet flushing and exposure to water with pathogens is expected to be low. Earlier research nevertheless showed that droplets generated by toilet flushing determine the exposure to *Cryptosporidium* and *Giardia* in household water (Medema *et al.* 1998).

The household water at site II is microbiologically safe for most pathogens but the safety margins are relatively low (0.4 to 1.3 log units for *Campylobacter* and viruses respectively) due to the limited DEC of the treatment system for different micro-organisms. Noroviruses were an exception. The mean concentration of Noroviruses (determined by RT-PCR) in the Lek Canal, the source of household water at site II, was estimated at 2,700/litre. Calculations showed that concentrations of Noroviruses in household water could reach values 30 times higher than the concentration that corresponds to the 10^{-4} infection risk. The results of the quantitative risk analysis are presented in Table 3. The estimated total infection risk at the different sites varies from $2.4 * 10^{-4}$ person^{-1} year^{-1} at site II, $4.4 * 10^{-5}$ at site III, $6.8 * 10^{-6}$ at site IV up to $8.9 * 10^{-8}$ at site I.

Microbiological stability and regrowth

The results of the microbiological stability and regrowth parameters are presented in Figure 1. Except for site II, household water was biologically less stable than drinking water. For example at site I the biofilm formation rate was as high as 500 pg ATP/cm^2.day (for drinking water <10 pg ATP/cm^2.day is recommended). The instability coincided with complaints of residents about the smell and colour of the water. At site III growth of *Legionella* in the household water system was observed. In one house concentrations of up to 2,000 cfu/l were found.

System operation and use

During the course of this study two incidents occurred at site II. A cross connection between the drinking water and household water system from a pipe that had been used to fill the household water system but had not been removed afterwards resulted in the introduction of household water into the potable water system. It is likely that in December 2001 about 200 residents in a section of the estate became ill after consuming drinking water that had been contaminated with household water (Fernandes *et al.* 2006). At a second incident in January 2002 a cross connection was found between the household water and drinking water systems in a single house. The water

Table 3 | Quantitative microbial risk assessment

			Treatment				
Sites	**Organisms (samples)**	**Source water C_{source} (n l^{-1}; range)[c]**	**Surrogates (samples)**	**DEC[d]**	**Household water C_{hhw} (n l^{-1})[e]**	**Exposure (n person^{-1} year^{-1})**	**Infection risk (person^{-1} year^{-1})**
Site I	Enteroviruses (6)	0.8 (0.012–3.3)	Somatic Coliphages (6)	6.1	$6.4{\cdot}10^{-7}$	$5.1{\cdot}10^{-11}$	$7.3{\cdot}10^{-13}$
	Rotavirus RCP[b] (6)	<18.4	Somatic Coliphages (6)	6.1	$<1.5{\cdot}10^{-5}$	$<1.2{\cdot}10^{-9}$	$<7.3{\cdot}10^{-10}$
	Norovirus RCP[b] (6)	<44.1	Somatic Coliphages (6)	6.1	$<3.5{\cdot}10^{-5}$	$<2.8{\cdot}10^{-9}$	$<2.8{\cdot}10^{-11}$
	Cryptosporidium (6)	5.9 (<0.03–18.5)	SSRC (66)	4.6	$1.5{\cdot}10^{-4}$	$8.2{\cdot}10^{-7}$	$3.4{\cdot}10^{-9}$
	Giardia (6)	29.8 (8.2–76)	SSRC (66)	4.6	$7.5{\cdot}10^{-4}$	$4.1{\cdot}10^{-6}$	$8.1{\cdot}10^{-8}$
	Campylobacter (6)	33 (<3–150)	*E. coli* (66)	>4.2	$> 2.1{\cdot}10^{-3}$	$> 1.8{\cdot}10^{-7}$	$> 3.5{\cdot}10^{-9}$
Site II	Enteroviruses (6)	0.039 (0.005–0.075)	F+ RNA phages (6)	1.2	$2.5{\cdot}10^{-3}$	$2.0{\cdot}10^{-7}$	$2.9{\cdot}10^{-9}$
	Rotavirus RCP[b] (6)	<31	F+ RNA phages (6)	1.2	2.0	$1.6{\cdot}10^{-4}$	$9.8{\cdot}10^{-5}$
	Norovirus RCP[b] (6)	2,700 ($<31–1.4{\cdot}10^{4}$)	F+ RNA phages (6)	1.2	1.7	$1.4{\cdot}10^{-2}$	$1.4{\cdot}10^{-4}$
	Cryptosporidium (12)	8.2 (<0.0–35)	*Cryptosporidium*	2.6	$2.1{\cdot}10^{-2}$	$1.2{\cdot}10^{-4}$	$4.8{\cdot}10^{-7}$
	Giardia (12)	95 (<0.0–950)	*Giardia*	3.6	$2.4{\cdot}10^{-2}$	$1.3{\cdot}10^{-4}$	$2.6{\cdot}10^{-6}$
	Campylobacter (7)	30	*E. coli* (36)	1.7	$6.0{\cdot}10^{-1}$	$5.2{\cdot}10^{-5}$	$10.0{\cdot}10^{-7}$
Site III	*Cryptosporidium* (6)	0.06 (<0.041–0.19)	ND[a]	NT[a]	$6.0{\cdot}10^{-2}$	$3.3{\cdot}10^{-4}$	$1.4{\cdot}10^{-6}$
	Giardia (6)	0.35 (0.1–1.1)	ND	NT	$3.5{\cdot}10^{-1}$	$1.9{\cdot}10^{-3}$	$3.8{\cdot}10^{-5}$
	Campylobacter (6)	<3	ND	NT	3.0	$2.6{\cdot}10^{-4}$	$5.0{\cdot}10^{-6}$
Site IV	Enteroviruses (6)	<0.004	Somatic Coliphages (6)	3.9	$<5.0{\cdot}10^{-7}$	$<4.0{\cdot}10^{-11}$	$<5.7{\cdot}10^{-13}$
	Rotavirus RCP[b] (6)	<12.9	Somatic Coliphages (6)	3.9	$<1.6{\cdot}10^{-3}$	$<1.3{\cdot}10^{-7}$	$<7.8{\cdot}10^{-8}$
	Norovirus RCP[b] (6)	<30.9	Somatic Coliphages (6)	3.9	$<3.9{\cdot}10^{-3}$	$<3.1{\cdot}10^{-7}$	$<3.1{\cdot}10^{-9}$
	Cryptosporidium (6)	<0.1	SSRC (44)	0.7	$<2.0{\cdot}10^{-2}$	$<1.1{\cdot}10^{-4}$	$<4.6{\cdot}10^{-7}$
	Giardia (6)	<0.29	SSRC (44)	0.7	$<5.8{\cdot}10^{-2}$	$<3.2{\cdot}10^{-4}$	$<6.3{\cdot}10^{-6}$
	Campylobacter (5)	3.4 (<0.3–7)	Enterococcs (44)	4.2	$2.1{\cdot}10^{-4}$	$1.83{\cdot}10^{-8}$	$3.49{\cdot}10^{-10}$

[a]NT = no treatment; ND = not determined.
[b]RCP = RNA containing particles: determined by RT-PCR in serial dilutions.
[c]C_{source} is the mean of the measured concentrations of a micro-organism in the source water.
[d]DEC is the mean elimination capacity (log units) of the treatment.
[e]C_{hhw} is the calculated concentration of a pathogenic micro-organism per litre of household water.

systems were wrongly connected to the mains in the street. A thorough inspection of all household water systems in the Netherlands on cross connections ordered by the Inspectorate highlighted a number of similar cases at other locations.

Before these incidents became known the inhabitants of site II and the other pilot locations in general were satisfied with the household water and considered it to be an ecologically sound product. An inquiry that was part of the research – the full data are not presented in this

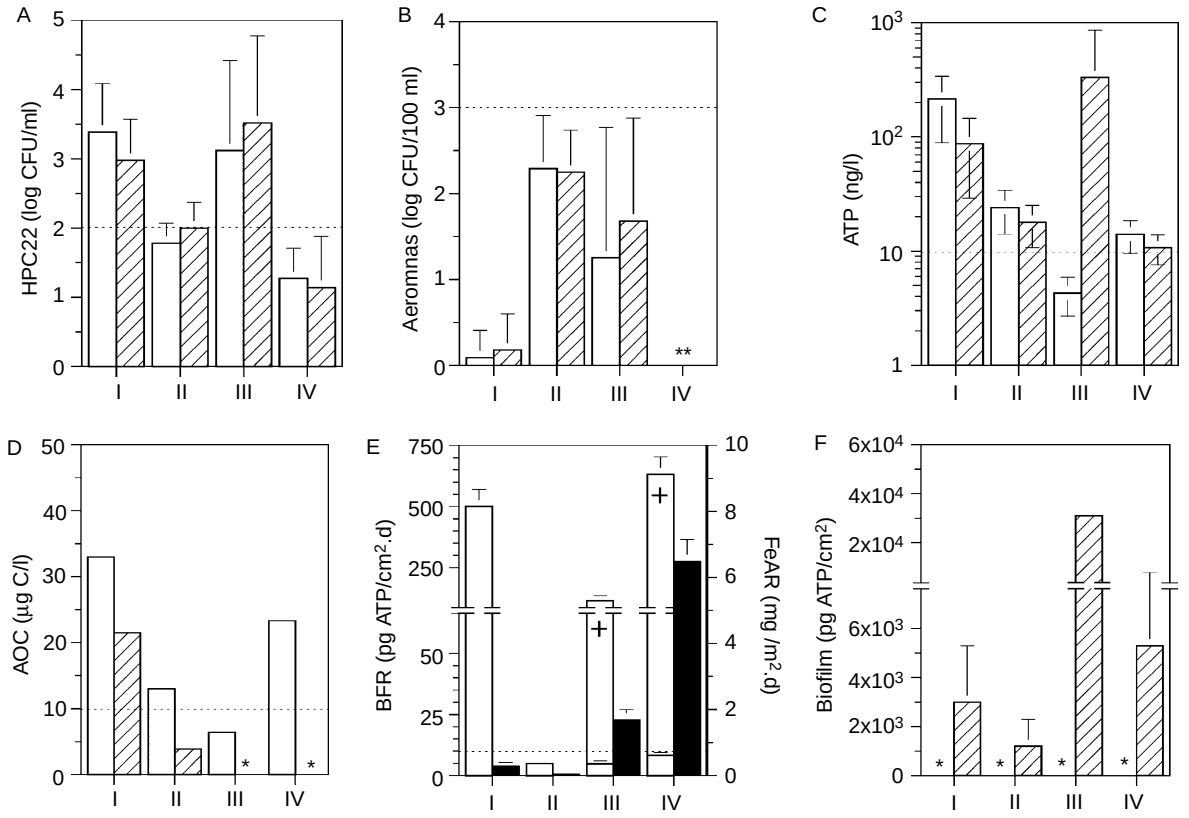

Figure 1 | Concentrations of bacteria, growth-promoting compounds and biofilms in four different types of household water. Open bars show data of treated water at the production plant; hatched bars show data at sites in the distribution area. Black bars in Figure 1E represent the iron accumulation rate (FeAR) as observed in the biofilm monitor supplied with treated water. *, no data; +, elevated BFR value observed after continued exposure. The FeAR values at these sites are values as observed in the period with elevated BFR. Dotted horizontal lines: Figure 1A: criterion for the heterotrophic plate count in drinking water during distribution (100 CFU/ml); Figure 1B: maximum value for *Aeromonas* in drinking water (1,000 CFU/100 ml); Figure 1C: reference value for ATP in drinking water (10 ng/l); Figure 1D: reference value for AOC in drinking water (10 µg AOC/l); Figure 1E: reference value BFR in treated water (10 pg ATP/cm^2.d) (Van der Kooij *et al.* 1999).

paper – showed that 80% of customers were satisfied. A Life Cycle Analysis was used to estimate the environmental benefits of dual water systems. The calculations showed that the environmental advantage is limited. For one household the annual benefit was not more than the equivalent of the petrol consumption of a 50 mile car drive.

EVALUATION

The results of this study show that the health risks linked to household water systems are mainly determined by the microbiological quality. Household water is not intended for human consumption. This means that it can be of a lower quality than potable water. Exposure to pathogens in household water is limited to direct contact with the skin and inhalation of aerosols. The objective is that the use of household water in addition to potable water should not exceed the infection risk of one per 10,000 inhabitants per year. This study shows that the (preliminary) 10^{-4} infection risk limit was exceeded in the case studies. At site II and site III exposure to household water aerosols during toilet flushing led to a higher risk of infection. Installation of additional disinfection (e.g. UV) would result in household water that meets the 10^{-4} infection risk goal.

Except for site II household water was biologically clearly less stable than drinking water. Complaints concerning colour and smell of household water and the presence of *Legionella* at site I and III respectively showed that the biological stability of household water is insufficient. Therefore certain requirements for the biological stability of household water are necessary. At least one biological

filtration step during production (e.g. rapid sand filtration) is recommended to improve biological stability.

The recommendations for additional treatment of household water (at least one disinfection step and a biological filtration step) will reduce the difference between household water and potable water. This study also shows that the environmental benefits of household water are limited. These findings lead to the conclusion that the public health risks and the economic costs of household water outweigh the benefits.

In addition, first practical experiences have showed that safe use of household water is not always warranted, because of the following reasons:

- accidental cross-connections between the potable and household water networks in the construction period;
- insufficient procedural guarantees for correct construction and operation of the dual water supply system;
- insufficient public information aimed at preventing the wrong use of household water or preventing wrong pipe connection in houses;
- insufficient information for installation companies to prevent the wrong construction inside houses.

After the incidents at site II all dual water projects in the Netherlands owned by water companies including the three mentioned in Table 1 were terminated. New plans for dual water supply were cancelled and household water was replaced by drinking water at the existing sites. Subsequently, most of the household water facilities at these sites have been dismantled.

HOUSEHOLD WATER SYSTEMS, NO OPTION IN THE NETHERLANDS

The Secretary of State has advised the Dutch Parliament to discourage the production and distribution of household water with dual water supply systems on a large scale. Dual water systems on a small scale are still allowed but (i) only when rainwater or groundwater is used as a source, (ii) when the household water is used for toilet flushing only and (iii) when it complies with the 10^{-4} infection risk. These criteria will be established as rules in the Dutch Water Supply Decree including specific obligatory means to safeguard compliance with the 10^{-4} infection risk.

ACKNOWLEDGEMENTS

This study was funded by the Ministry of Housing, Spatial Planning and the Environment. The authors are grateful to all the water companies involved and the association of house owners in Waterwijk Amsterdam for their contributions to the project. Also the technical assistance of Wim Hijnen, Hans Vrouwenvelder and Margreet Mons is acknowledged.

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First received 13 July 2005; accepted in revised form 22 November 2006