Aquifer recharge with reclaimed water: life-cycle assessment of hybrid concepts for non-potable reuse

M. Staub, H. Thouement, C. Remy, U. Miehe, G. Grützmacher, P. Roche, E. Soyeux and B. David

ABSTRACT

Aquifer recharge with reclaimed water is a promising means to store and supply on demand reclaimed water of high quality for further non-potable reuse. The reuse applications may include indirect agricultural or landscape irrigation, saltwater intrusion barriers, subsidence mitigation or aquifer replenishment. As an alternative to high-pressure or double-membrane systems, hybrid schemes consisting of a disinfection/filtration step prior to aquifer recharge were assessed in this study regarding their environmental footprint and energy efficiency. A simplified life-cycle assessment (LCA) for a hypothetical case study in a water-scarce country was conducted to compare these hybrid schemes to a double-membrane system working under similar conditions. The results show that there is a significant margin for lowering the environmental impact, energy demand and operational costs if non-potable water quality is targeted. While the hybrid schemes outperform high-pressure membranes for these factors, land footprint and final water quality also need to be considered in the choice of solution for specific conditions.

Key words | disinfection, filtration, LCA, life-cycle assessment, managed aquifer recharge, non-potable reuse

M. Staub (corresponding author)
Veolia Germany, Technical Department,
Walter-Köhn Str. 1a, Leipzig 04356,
Germany
E-mail: *matthias.staub@veolia.com*

H. Thouement
C. Remy
U. Miehe
G. Grützmacher
Kompetenzzentrum Wasser Berlin,
Cicerostr. 24, Berlin 10709,
Germany

P. Roche
E. Soyeux
Veolia Environnement Recherche et Innovation,
Chemin de la Digue, BP76,
Maisons-Laffitte Cedex 78603,
France

B. David
Veolia France, Direction Technique et Performance,
1, Rue Giovanni Battista Pirelli, Immeuble Giovanni Battista B, Saint Maurice 94410,
France

INTRODUCTION

Against a background of population growth, increasing industrialization and urbanization as well as climate change, wastewater reuse is increasingly considered as a possible alternative water source for diverse non-potable uses (Asano 1998). A crucial factor is to define the water quality requirements for specific uses. However, it also needs to be considered that reclaimed water is usually available at relatively constant flows throughout the year, while the demand for reclaimed water is seasonal. Therefore, the question of reclaimed water storage is also essential.

Most of the aquifer recharge applications of wastewater reuse so far rely on high-pressure membrane systems or even double-membrane and advanced oxidation processes as pre-treatment. However, when non-potable reuse is targeted or the replenishment of a threatened aquifer is planned, recharge with high-quality non-potable water could be envisaged (Aertgeerts & Angelakis 2003), as acknowledged by the legislation of several countries. The goal of this study was to identify treatment schemes including aquifer recharge (Figure 1) that meet the requirements for non-potable re-use and to analyse the environmental impact in comparison to traditional water re-use schemes using double membranes.

METHODS

Selection of treatment trains and initial–final water qualities

A defined secondary effluent (SE) was considered as input flow for this conceptual study on the basis of a worldwide survey of typical SE water qualities (total suspended solids, TSS: 19 mg/L; turbidity: 9 NTU; chemical oxygen demand,

doi: 10.2166/wrd.2014.037

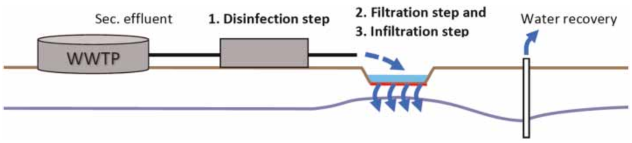

Figure 1 | Schematic of a typical 'hybrid scheme' as considered in this study.

COD: 61 mg/L; N-NH_4: 7 mg/L; N-NO_3: 9 mg/L; P-PO_4: 6 mg/L; total coliforms (TCF): 5×10^5/100 mL; *Escherichia coli*: 10^5/100 mL). The major legislations from WHO, USEPA and Australian guidelines were considered to define the water quality to be reached by these hybrid treatment schemes (NRMMC-EPHC-AHMC 2006; WHO 2006; NRMMC-EPHC-NHMRC 2009; USEPA 2012). Particulate pollution (TSS), biological pollution (biochemical oxygen demand, BOD_5) and microbiological contamination (TCF) were the only quality requirements for unrestricted non-potable reuse which were consistently defined in the above-mentioned guidelines (TSS < 10 mg/L, BOD_5 < 20 mg/L and less than 1 faecal coliform (FCF)/100 mL). Besides pathogen removal, all other processes occurring during saturated subsurface passage in the aquifer were not taken into account due to their site specificity. Especially as the targeted values in suspended solids (10 mg/L) and microbiological contaminants (1/100 mL) require significant disinfection and filtration processes as pre-treatment. The targeted value corresponds to calculated 5-log removal of microbiological pollution. This includes 2 log for ozonation (Bahr *et al.* 2007), >3 log for UV applying a fluence of 400 J/m² (Lazarova *et al.* 1999), up to >4 log for ultrafiltration (UF) (Wang *et al.* 2005), >1.5 log from infiltration ponds/slow sand filtration (Bali *et al.* 2011) and another 1.5 log removal for a subsurface passage of minimum 5 days (Schijven *et al.* 1998, 1999, 2000; DeBorde *et al.* 1999; Partinoudi & Collins 2007). Five schemes that fulfil the requirements for unrestricted non-potable reuse were selected on the basis of a large review of typical pollutant removal efficiencies found in the literature (Asano 1998; Salgot *et al.* 2002; Amy *et al.* 2006; Dillon *et al.* 2008; DWA 2008) and compared with a double-membrane system (UF + NF) operating with similar input qualities, but with direct reuse without aquifer storage (Table 1). Thus, a direct comparison is not possible, other than to say UF – NF achieves better water quality (e.g. also reduces salinity).

Considered hypothetical case study

Owing to the lack of existing data, and to enable an easier comparison of different schemes, a hypothetical case study was considered based on real data from Veolia-operated sites. The case study was chosen to be located in Morocco as the Mediterranean region is expected to be a potential area for application. This choice impacts the emission factors (e.g. for the electricity mix) as well as the transport distances for raw and engineered material supply.

The plant was designed with a size of 50,000 population equivalent (PE), with a considered design wastewater flow of 6,250 m³/d (2.3 Mm³/y) based on a 125 L/day/PE wastewater generation. The wastewater quality is based on the 75th percentile of the SE quality review performed, as listed above. Additional boundary conditions are no need for salinity reduction, e.g. due to the specific crop to be irrigated and no major heavy metal input into the municipal wastewater treatment plant. The hypothetical case study consists of a tertiary water reclamation and aquifer recharge facility next to an existing wastewater treatment plant (for main design parameters, see Table 2). The possibility to recharge the aquifer and sufficient land availability are taken for granted.

Table 1 | Five hybrid treatment trains and double-membrane scheme selected for simplified LCA

Treatment train	Disinfection	Filtration	Infiltration	Min. aquifer storage	Pathogen removal
#1	Ozone		Infiltr. pond	5 days	>5 log
#2	UF	UF	Injection	5 days	>5.5 log
#3	Ozone	SSF	Injection	5 days	>5 log
#4	UF	UF	Infiltr. pond	5 days	>7 log
#5	UV		Infiltr. pond	5 days	>6 log
#6	UF	UF + NF	None	No storage	>6 log

UF, Ultrafiltration; SSF, Slow sand filtration; NF, Nanofiltration.

Table 2 | Main design parameters of the treatment steps for the simplified LCA

Treatment step unit	Life-time	Flow	Number of units	Energy (kWh/m³)	Other
Ozonation unit	15 years	6,250 m³/d (100% flow recov.)	1 O_3 generator	0.19	O_3 dose: 0.6 mg/mg of DOC
Ultraviolet lamps	3 years		49 UV lamps	0.05	UV dose: 1,000 J/m² (fluence appr. 350–450 J/m²)
UF membrane units	7 years	57 m³/d/module (90% flow recov.)	217 modules	0.17	Coagulant used: $FeCl_3$ Cleaning agents: NaOH, H_2SO_4, NaOCl, HCl, Citric acid, Tenside
NF membrane units	7 years	13 m³/d/module (90% flow recov.)	391 modules	0.65	
Slow sand filters	20 years	2.4 m/d infiltration rate	4 SSF (+1 backup)	–	Filter thickness: 1 m, tot. surface 2,600 m² Cleaning frequency: 12 a^{-1}
Infiltration ponds	30 years	0.43–0.86 m/d infiltration rate	4 IP (+2 for rotations)	–	Sand layer: 0.30 m, tot. surface 1.3–2.8 ha Cleaning frequency: 2–6 a^{-1}
Injection wells	30 years (pump: 12 y)	1,265–1,563 m³/d	4 wells	0.02	Pump TDH: 4 m; Well depth: 20 m Well diameter: 250 mm
Recovery wells				0.11	Pump TDH: 25 m

DOC, Dissolved organic carbon; TDH, Total dynamic head.

Methodology for the life-cycle assessment

To compare the different hybrid solutions, a life-cycle assessment (LCA) was conducted. LCA is a standardized method to quantify various environmental impacts of a process or product. It enables monitoring of all direct and indirect impacts of a given process and reveals a shift of environmental burdens to other areas of the environment or to other geographical areas. The life cycle of a system is the 'consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal' (ISO 14040 2006).

As applied to water and wastewater systems, the LCA evaluates the different stages of the life of the infrastructure (mainly construction, use and decommissioning) and includes the linked indirect activities for operation, such as electricity production, transport and chemicals used (Renou 2006). For assessing the life cycle impacts of a given process, aggregated inputs and outputs of the system are evaluated with specific environmental indicators. In the present paper, only the impact on climate change (carbon footprint) will be presented, while the study also assessed human toxicity and terrestrial acidification. Substance flow models for all assessed treatment schemes are implemented and evaluated using the LCA software 'Umberto®5.6' (IFU & IFEU 2009). The considered emission factors for background processes (electricity, chemicals and infrastructure) are compiled from the ecoinvent database (Ecoinvent 2010) complemented by a Veolia-internal database.

In addition to traditional LCA indicators, the land footprint (ha of land/Mm³ of reclaimed water per year) and the electricity demand or energy intensity (kWh/m³) of the different treatment trains were assessed. Figure 2 gives an overview of the system boundaries, the processes considered and the indicators evaluated.

RESULTS AND DISCUSSION

Comparative electricity demand

The electricity demand of treatment trains #1–4 is approximately 0.20–0.25 kWh/m³ and thus up to five times less than combined ultrafiltration and nanofiltration (#6) (Figure 3). The combination of UV with infiltration ponds (#5) has even lower energy demand levels with 0.08 kWh/m³. It is noteworthy that water pumping from the recharged

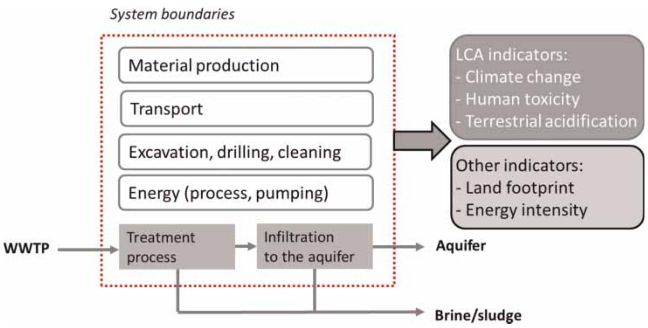

Figure 2 | LCA boundaries considered in this study.

aquifer can significantly increase the electricity demand of the treatment trains. Here, a 25 m pump total dynamic head was considered (Table 2), and the wells' energy demand may amount to up to 30% (#1–4) or even 60% of the total energy demand (#5). Thus, storing the water into aquifers with a deep piezometric surface will not be economically favourable compared to using more shallow or surface water resources. At an abstraction depth of 50 m, the electricity demand for water abstraction will exceed that of the treatment itself (schemes 1–5).

Comparative carbon footprint

Most hybrid treatment trains have comparable CO_2 emissions of around 0.20 kg CO_2eq/m³ (Figure 4), with UV disinfection and infiltration (#5) emitting less CO_2 (around 0.1 kg CO_2eq/m³). Nanofiltration (#6) increases the CO_2 emissions three to five fold (around 0.7 kg CO_2eq/m³). Electricity is clearly the dominant factor for CO_2 emissions related to these treatment trains. It represents 70–75% of the total life cycle carbon footprint of the treatment trains, except for UV disinfection and infiltration (#5) where it represents only 51% of the total carbon footprint, and nanofiltration (#6), with 94% of life cycle emissions. Another important contribution to CO_2 emissions for the treatment trains with infiltration ponds (#1, #4 and #5) is construction – amounting up to 46% for UV disinfection and infiltration (#5). Chemicals also represent a significant source of CO_2 emissions for the treatment trains involving membranes (#2, #4 and #6). Similar conclusions were obtained for LCA of advanced phosphorous removal during wastewater treatment by Remy *et al.* (2014).

Comparative land footprint

Figure 5 shows the land footprint of each proposed scheme. If space availability is an issue, solutions involving membranes (#2 and #6) or slow sand filters (#3) should be preferred as they need only very little space. On the whole, highly urbanized areas may not be the primary target of hybrid reuse schemes, which will probably

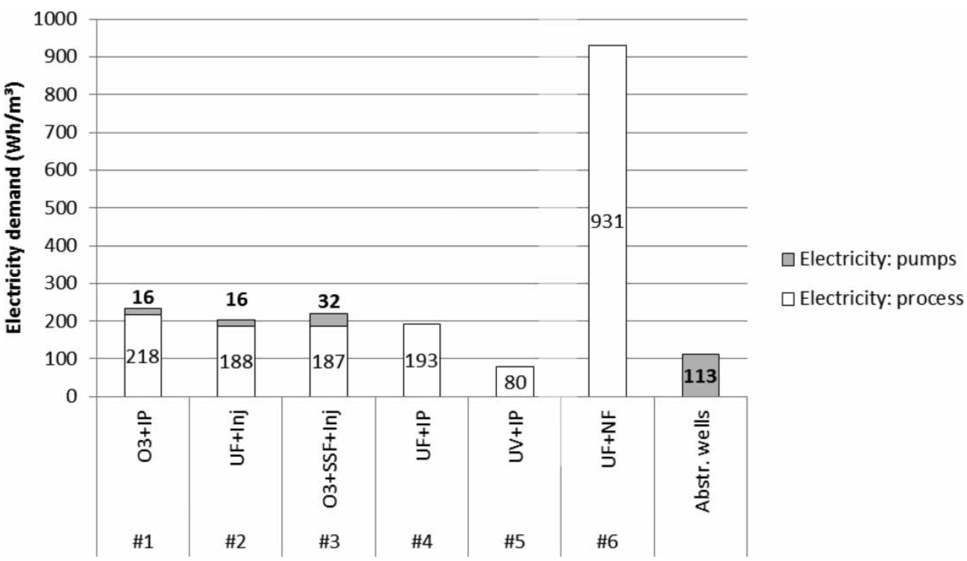

Figure 3 | Electricity demand of the selected treatment trains (NF: without brine disposal).

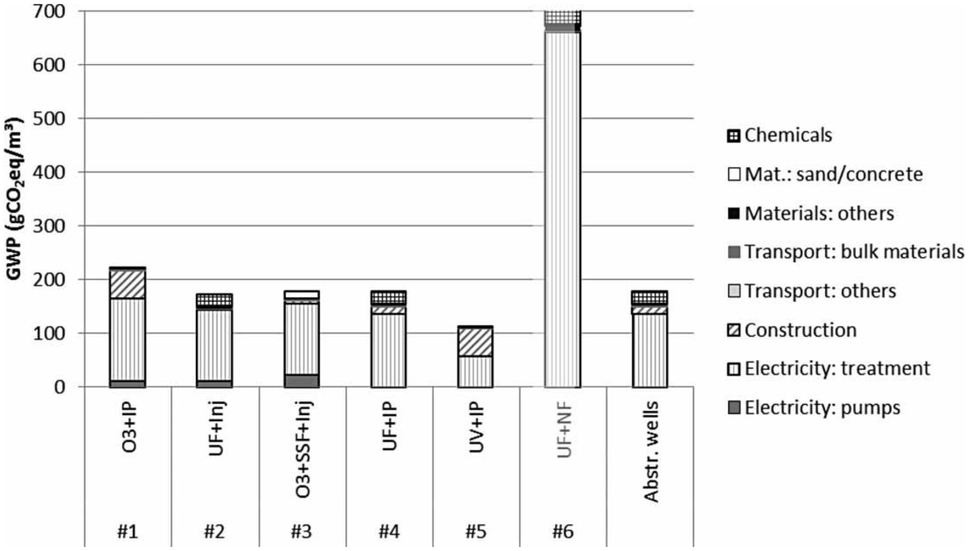

Figure 4 | Global warming potential for the selected treatment trains.

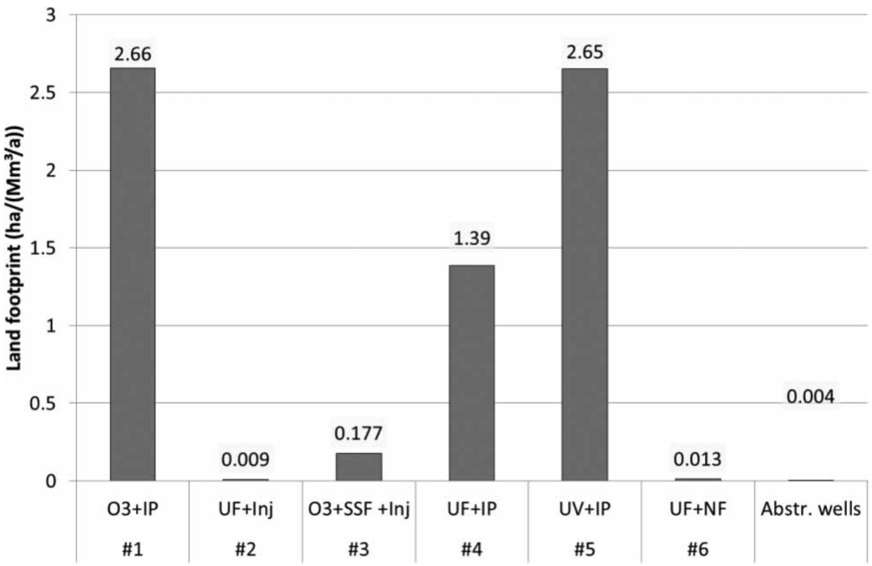

Figure 5 | Land footprint of the selected treatment trains.

choose high-technology, high-energy demanding equipment providing reclaimed water of potable quality.

CONCLUSIONS

All five proposed hybrid treatment trains are capable of supplying water of high-quality fit for all non-potable reuses, and the combination of disinfection, filtration and aquifer passage proved to be an efficient combination for removing suspended solids, residual BOD and microbiological contaminants to the required degree. The environmental performance of the treatment trains was compared in terms of carbon footprint (Figure 4), but also electricity demand (Figure 3) and land footprint (Figure 5). Both the electricity demand and carbon footprint of hybrid schemes were found to be considerably lower than for a double-membrane system, besides offering an additional storage solution in the aquifer without evaporation losses and direct anthropogenic or climatic impact.

Thus, there is a significant margin for lowering the environmental impact, energy demand and operational costs (not shown) if non-potable water quality is sufficient for the reuse goal. While the legal context and social acceptability may represent barriers for this intended recharge of non-potable water to the aquifer, one may question the necessity to use water of potable quality for non-potable reuse, saline intrusion control or land subsidence mitigation if alternative high-quality non-potable water solutions are available.

ACKNOWLEDGEMENTS

The project OXIMAR-1 was funded by Veolia Water. The authors gratefully acknowledge not only financial support but also technical guidance and fruitful discussions with colleagues of Veolia Eau Technical Direction (VE-DT), VWS&T Corporate Marketing Department and Veolia Environnement Recherche et Innovation (VERI) in the course of the project.

REFERENCES

Aertgeerts, R. & Angelakis, A. 2003 *State of the Art Report: Health Risks in Aquifer Recharge Using Reclaimed Water*. Report WHO/SDE/WSH/03.08, Water Sanitation and Health Programme, WHO, Geneva, Switzerland and WHO Regional Office for Europe, Copenhagen, Denmark.

Amy, G., Carlson, K., Collins, M. R., Drewes, J. E., Gruenheid, S. & Jekel, M. 2006 Integrated comparison of biofiltration in engineered versus natural systems. In: *Recent Progress in Slow Sand Filtration and Alternative Biofiltration Processes*, (R. Gimbel, N. J. D. Graham & M. R. Collins, eds). IWA Publishing, London, UK, pp. 3–11.

Asano, T. 1998 *Wastewater Reclamation and Reuse*. Technomic Publishing, Lancaster, PA.

Bahr, C., Schumacher, J., Ernst, M., Luck, F., Heinzmann, B. & Jekel, M. 2007 SUVA As control parameter for the effective ozonation of organic pollutants in secondary effluent. *Water Science and Technology* **55** (12), 267–274.

Bali, M., Gueddari, M. & Boukchina, R. 2011 Removal of contaminants and pathogens from secondary effluents using intermittent sand filters. *Water Science and Technology* **64** (10), 2038–2043.

DeBorde, D. C., Woessner, W. W., Kiley, Q. T. & Ball, P. 1999 Rapid transport of viruses in a floodplain aquifer. *Water Research* **33**, 2229–2238.

Dillon, P., Page, D., Vanderzalm, J., Pavelic, P., Toze, S., Bekele, E., Sidhu, J., Prommer, H., Higginson, S., Regel, R., Rinck-Pfeiffer, S., Purdie, M., Pitman, C. & Wintgens, T. 2008 A critical evaluation of combined engineered and aquifer treatment systems in water recycling. *Water Science and Technology* **57** (5), 753–762.

DWA 2008 *Treatment Steps for Water Reuse*. Report of the German Association for Water, Wastewater and Waste. Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V., Hennef, Germany.

Ecoinvent 2010 *Ecoinvent Data v2.2*, Ecoinvent Reports No. 1–26. Swiss Center for Life Cycle Inventories, Dübendorf, Switzerland. http://www.ecoinvent.org.

IFU & IFEU 2009 *Umberto – Software for Operational Substance Flow Management, Version Umberto 5.6*. Institut für Umweltinformatik GmbH und Institut für Energie- und Umweltforschung Heidelberg GmbH, Heidelberg/Hamburg, Germany.

ISO 14040 2006 *Environmental management – Life-Cycle Assessment – Principles and Framework*. International Standardization Organization, Geneva, Switzerland.

Lazarova, V., Savoye, P., Janex, M. L., Blatchey III, E. R. & Pommepuy, M. 1999 Advanced wastewater disinfection technologies: state of the art and perspectives. *Water Science and Technology* **40** (4–5), 203–213.

NRMMC-EPHC-AHMC 2006 Australian guidelines for water recycling: managing health and environmental risks (phase 1). In: (NWQMS Document 21) Natural Resource Management Ministerial Council, Environment Protection and Heritage Council, and Australian Health Ministers' Conference, Canberra, Australia.

NRMMC-EPHC-NHMRC 2009 Australian guidelines for water recycling: managing health and environmental risks (phase 2). In: Managed Aquifer Recharge. (NWQMS Document 24) Natural Resource Management Ministerial Council, Environment Protection and Heritage Council and National Health and Medical Research Council, Canberra, Australia.

Partinoudi, V. & Collins, M. R. 2007 Assessing RBF reduction/removal mechanisms for microbial and organic DBP precursors. *Journal of American Water Works Association* **99** (12), 61–71.

Remy, C., Miehe, U., Lesjean, B. & Bartholomäus, C. 2014 Comparing environmental impacts of tertiary wastewater treatment technologies for advanced phosphorus removal and disinfection with life cycle assessment. *Water Science and Technology* **69** (8), 1742–1750.

Renou, S. 2006 Analyse de cycle de vie appliqué aux systèmes de traitement des eaux usées (Life cycle analysis applied to

wastewater treatment systems). PhD Thesis, Institut National Polytechnique de Lorraine, Ecole Nationale Supérieure des Industries Chimiques, Ecole Doctorale RP2E, France.
Salgot, M., Folch, M., Huertas, E., Tapias, J., Avellaneda, D., Girós, G., Brissaud, F., Vergés, C., Molina, J. & Pigem, J. 2002 Comparison of different advanced disinfection systems for wastewater reclamation. *Water Science and Technology: Water Supply* **2** (3), 213–218.
Schijven, J. F., Hoogenboezem, W., Nobel, P. J., Medema, G. J. & Stakelbeek, A. 1998 Reduction of FRNA-bacteriophages and faecal indicator bacteria by dune infiltration and estimation of sticking efficiencies. *Water Science and Technology* **38** (12), 127–131.
Schijven, J. F., Hoogenboezem, W., Hassanizadeh, S. M. & Peters, J. H. 1999 Modeling removal of bacteriophages MS2 and PRD1 by dune recharge at Castricum, Netherlands. *Water Resources Research* **35**, 1101–1111.
Schijven, J. F., Medema, G., Vogelaar, A. J. & Hassanizadeh, S. M. 2000 Removal of microorganisms by deep well injection. *Journal of Contaminant Hydrology* **44**, 301–327.
USEPA 2012 *Guidelines for Water Reuse. Guidelines of the United States Environmental Protection Agency*. USEPA, Cincinnati, OH, 642 pp.
Wang, X. C., Qiu, F. G., Xue, X. P. & Lu, X. 2005 Application of a virological tracer method for the assessment of pathogen removal by physicochemical treatment and chemical disinfection. *Water Science and Technology* **52** (8), 205–212.
WHO 2006 *WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater*, Vols I–IV. Report of the World Health Organization, WHO, Geneva, Switzerland.

First received 20 May 2014; accepted in revised form 26 October 2014. Available online 10 December 2014