Valuing the subsurface pathogen treatment barrier in water recycling via aquifers for drinking supplies

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Abstract

A quantitative microbial risk assessment was performed at four managed aquifer recharge (MAR) sites using the same risk-based approach that is used for public water supplies. For each of the sites, the aquifer treatment barrier was assessed for its $\log_{10}$ removal capacity much like for other water treatment technologies. The use of aquifers as a treatment step to reduce pathogen numbers is considered in a standardised form along with other ~~engineered~~ treatments. This information was then integrated into a broader risk assessment to determine the human health burden from the four MAR sites. For the Australian and South African cases, managing the aquifer treatment barrier was found to be critical for the schemes to have low risk. For the Belgian case study, the large treatment trains both in terms of pre- and post- aquifer recharge ensures that the risk is always low. In the Mexico case study site the risk was high due to the lack of pre-treatment and the low residence times of the recharge water in the aquifer. A further sensitivity analysis of the risks demonstrated that human health risk can be managed if aquifers are integrated into a treatment train to attenuate pathogens. However, reduction in human health disease burden (as measured in disability adjusted life years, DALYs) varied depending upon the number of pathogens in the recharge source water. The beta-Poisson dose response curve used for translating rotavirus and *Cryptosporidium* numbers into DALYs coupled with their slow environmental decay rates means poor quality injectant leads to aquifers having reduced value to reduce DALYs. For these systems, like the Mexican case study, longer residence times are required to meet their DALYs guideline for drinking water.

Introduction

Water reuse is increasingly regarded as an appropriate and cost effective option for augmentation of urban water supply needs (NRMMC-EPHC 2006). Drivers for the increased reuse of water include severe water shortages in dry periods, climate change, stricter regulations on waste discharge to the receiving environment and growing urban populations. Furthermore, in the developing world, unintentional water reuse may also exist as result of lack of sanitation (Jimenez and Asano 2008), and limited wastewater treatment facilities.

Climate change and increasing urbanisation has had a detrimental effect on groundwater resources which has resulted in an increasing worldwide interest in the recharge of aquifers for augmenting urban drinking water supplies (Dillon 2005). Aquifer recharge can utilise a variety of non-traditional source waters including urban stormwater and reclaimed water from sewage effluent. The role of the aquifer in the treatment train has not been considered with the same rigor as engineered components such as filtration or disinfection, even though it may lead to large improvements in water quality (Dillon and Toze 2005). It has been documented that pathogens are actively removed during passage through aquifers (Gordon and Toze 2003, Nasser and Oman 1999, Toze *et al.* 2004, Yates *et al.* 1990) yet this information is often still to be incorporated into the role of aquifers as active treatment systems. Consequently many jurisdictions do not integrate the subsurface treatment into the entire risk management strategy for potable water supplies. Hence the objectives of this paper are:

- To determine the value of the aquifer treatment barrier at four drinking water case study sites.
- To perform a quantitative microbial risk assessment on the case study sites which use water reclamation via aquifers to augment a potable supply.
- To standardise the valuing of the aquifer in relation to the other engineered treatment barriers
- To develop an approach for integrating aquifer treatment with engineered treatment systems in assessment of drinking water supplies.

With new approaches such as water recycling via aquifers, sound risk management becomes even more important. Australia has been active in developing new approaches to managing risks associated with recycled water quality. In 2006, the Natural Resource Management Ministerial Council and the Environment Protection and Heritage Council released the Australian G+uidelines for Water Recycling: Managing Health and Environmental Risks (Phase 1) (NRMMC-EPHC 2006) and subsequently in 2008, released its Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2A – Augmentation of Drinking Water Supplies. Phase 2B Stormwater Harvesting and Reuse and Phase 2C Managed Aquifer Recharge have also been released but are public consultation drafts in 2009) (EPHC-NHMRC-NRMMC 2008 b, c). These guidelines form the basis of an integrated methodology for managing human health and environmental risks by providing guidance and acceptability criteria for a range of risks common across many managed aquifer recharge (MAR) configurations. These parallel international developments in the World Health Organisation Water Safety Plans (WHO 2004; 2005).

In other countries such as Mexico there is already extensive use of wastewater for irrigation, some of which infiltratates into the underlying aquifers that are used as drinking sources (Jimenez and Chavez 2004). It is therefore important to assess the risks of these practices to human health and to move from unintentional reuse to managed systems. In this regard, local standards to promote and control aquifer recharge have been proposed (e.g. NOM-014-CNA-2003). Similarly, the RECLAIM WATER EC project was developed to share knowledge on current practices at selected aquifer recharge sites (Kôpak *et al.* 2007; Le Corre *et al.* 2007), and by this cooperation will contribute to develop sound risk-based management approaches to aquifer recharge.

Case Study Sites

This study considers four case studies that form part of the larger RECLAIM WATER project. Each site utilises a non-traditional water source and an engineered water treatment train coupled to an aquifer recharge system for augmenting urban drinking water supplies. A diagram of the study sites is given in Figure 1. Each treatment train was assessed using a quantitative microbial risk assessment approach and the aquifer treatment contribution compared across the four case study sites. Special attention has been given to the contribution of the aquifer barrier within the broader treatment train and its importance in managing human health risks.

The treatment trains and important attributes of the four case studies: Tula Valley (Mexico); Parafield (Australia); Atlantis (South Africa) and Wulpen (Belgium) are summarised in Table 1. These range from primary treatment with almost total reliance on the subsurface passage and residence time for water quality improvement at Tula Valley to advanced tertiary treatment at Wulpen where there is no reliance on the aquifer for water quality improvement. At the other two sites the aquifer plays an important complementary role to the engineered treatment systems. Though the case study sites have very different treatment trains these water reuse systems share the similar seven key system components listed in Table 1. Each site is further described briefly below.

The Tula valley site is located 100 km north of Mexico City and has received untreated wastewater from Mexico City since 1986. The Tula valley is a semiarid area with an expanded economy due to the availability of wastewater used for irrigation (Jimenez 2004). It has been estimated that ~50 m^3/s are used for irrigation in the area and as a result the local aquifer is being recharged at ~25 m^3/s due to the infiltration of untreated wastewater from irrigation channels, storage dams and excess water used for irrigation (Jimenez and Chavez, 2004). This infiltrated wastewater is hydraulically connected to local springs (aquifer residence time 20-40 days) that are used as drinking water supplies (Jimenez and Chavez, 2004). This is the largest known case of indirect wastewater reuse for human consumption in the world. In this study only the Cerro Colorado spring is considered which currently produces 0.4 m^3/s of potable water. Post-treatment includes chlorination to remove pathogens. Furrow irrigation of untreated effluent occurs within 20m of the spring. A wall surrounds the spring to ensure there is no direct surface discharge of effluent into the spring.

The Parafield aquifer storage transfer and recovery (ASTR) site is located in a suburb of Adelaide, South Australia. Urban stormwater from a mixed residential and industrial catchment is passed through a constructed reedbed prior to recharge via injection wells into a confined limestone aquifer. Water is recovered via separate wells after a mean residence time in the aquifer of 270 days (Kremer *et al*. 2009). Currently the site is managed as a trial to determine the suitability of the recovered water for drinking supplies. Post-treatment options are still being considered and may include UV and chlorine disinfection prior to entering the drinking water distribution system. Further details of the hydrogeology (Pavelic *et al.* (2004); Kremer *et al.* (2009)) as well as the development of the risk assessment and management plan (Swierc *et al.* (2005); Page *et al.* (2008; 2009)) have been reported.

The Atlantis site is located near Cape Town, in the semiarid southwest coast of South Africa. Secondary treated reclaimed water, together with wetland-treated urban storm water from a residential catchment is recharged to an unconfined sandy aquifer. Pre-treatment includes secondary wastewater treatment (activated sludge) prior to blending with urban stormwater flows and passing through an ~~constructed~~ artificial wetland. Water is infiltrated by means of two recharge basins, has a residence time in the aquifer of approximately one year prior to recovery by means of two well fields. Poor quality storm water from industrial zones is pumped into a coastal recharge basin which also forms a barrier between the extraction well fields and the sea to prevent saline intrusion. Post treatment involves water softening and chlorination before water is blended with Cape Town supplied mains water entering the drinking water distribution system.

The Wulpen site is located at the Flemish coast, and it has been developed to augment drinking water supplies from the aquifer at St. André and to prevent sea water intrusion. Tertiary (reverse osmosis) treated effluent is recharged to an unconfined sandy aquifer via an infiltration basin and recovered via a series of extraction wells after a residence time of ~35 days. Post treatment includes aeration, rapid sand filtration and UV disinfection prior to supply to the drinking water network.

Methods for risk assessment and valuing aquifer treatment

The microbial risk assessment methodology used follows the approach outlined in WHO (2004) and NRMMC-EPHC (2006). The traditional approach to identifying tolerable risk has been to define maximum levels of infection or disease. However, this approach fails to consider the varying severity of outcomes associated with different hazards. This shortcoming can be overcome by measuring severity in terms of disability adjusted life years (DALYs). DALYs have been used extensively by agencies such as the World Health Organization (WHO) to assess disease burdens (WHO 2004) and is the approach adopted in this study. Three representative pathogens; rotavirus, *Cryptosporidium* and *Campylobacter*, were used to assess the risk of viruses, protozoa and bacteria as described in WHO (2004) and EPHC-NHMRC-NRMMC (2008a). As the risk estimates are probability distribution functions, the mean, median and 95th percentile were routinely calculated for each pathogen risk. The tolerable mean risk adopted is 10^{-6} DALYs per person per year (WHO 2004).

For the case study sites discussed in this paper, qualitative residual risk assessments have been summarised as part of the RECLAIM WATER project (Ayuso-Gabella *et al.* 2007). In furthering the qualitative understanding of the pathogenic hazards at each site, a quantitative microbial risk assessment was performed to determine the residual risk of each case study and value of the aquifer treatment. The residual risks are risk probability estimates assuming nominal operating conditions i.e. where source waters are not exposed to unusual hazard inputs and treatment processes are operating according to specifications.

The risk models for simulating hazard reduction, consumption, infection and disease burden (expressed as DALYs, Disability Adjusted Life Years) were constructed using MS Excel program [2003] enhanced with @Risk Industrial v. 4.5 [Palisade Corp, USA].

A quantitative probability distribution function (PDF) describing each engineered treatment barrier was adopted from literature for each pathogen. In these situations a single triangular distribution was considered to be a useful representation of the barrier (Smeets *et al.* 2006). The triangular distribution was defined by a minimum, most likely and maximum $\log_{10}$ removal value (Smeets *et al.* 2006; EPHC-NHMRC-NRMMC 2008a) and are shown in Table 2. For the aquifer treatment barrier, the product of two PDFs; the aquifer residence time and a daily pathogen decay rate (expressed in $\log_{10}$ / day) were used to calculate the $\log_{10}$ removal value. Each of these treatment efficacy distributions were subsequently used in the Monte Carlo simulations to calculate the residual risk.

Once the residual risks were calculated for each MAR scheme a sensitivity analysis was performed which standardises the factors which affect risk and is termed the factor sensitivity (FS) (Zwietering and van Gerwen 2000). For each MAR scheme the residual risk was then recalculated in the absence of each barrier in turn (such as the aquifer treatment barrier). The FS is a ratio calculated by dividing the revised residual risk estimate (in DALYs) when a factor (e.g. a treatment step) is removed from the treatment train (denoted *N(Barrier)*), by the baseline mean risk, *N(Mean)* also in DALYs from the residual risk assessment and then $\log_{10}$ transforming the ratio.

$$FS = \log_{10}\left(\frac{N(Barrier)}{N(Mean)}\right)$$

Higher FS values means the factor has a larger effect on risk. Following assessment of FS a risk-based approach for determining suitable aquifer residence times for MAR schemes is proposed. Aquifer treatment uses the surrogate parameter, aquifer residence time to estimate the value of the aquifer treatment as part of the multi barrier system. Simulations of changes in the aquifer residence time allow the aquifer barrier to be quantified and compared to the acceptable risk, 1.0×10^{-6} DALYs. This allows the determination of a required average residence time and associated monitoring can be utilised to manage this barrier within the treatment system.

Results

Aquifer barrier treatment characterisation

Aquifer treatment characteristics were derived from the PDFs of the residence time in the aquifer and the reported $\log_{10}$ decay rates for pathogens (Table 4) based on the work by Toze *et al.* (2009) at the Australian site. No data were available for pathogen attenuation rates at the other sites and as this source water had the lowest mean temperature of all sites, and native groundwater was more anoxic than other sites, this is regarded as a conservative assumption. The aquifer and engineered treatment barrier characteristics are reported as $\log_{10}$-removals (Table 3) which conveys the order of magnitude of the removal for each of the reference pathogens. Removal $\log_{10}$ values for each treatment barrier were considered additive. All $\log_{10}$ removal values accredited to aquifers were capped at a maximum of 6.0 $\log_{10}$ consistent with the reported values for engineered treatments in EPHC-NHMRC-NRMMC (2008a). Each

Comment [BG1]: why cap at 6 log ? It is not supported by maximum counts or real data as far as I know?

of the MAR sites placed a different value on the aquifer removal characteristics compared to the engineered treatments. Tula Valley relied almost exclusively on the aquifer, where as Wulpen had extensive redundancy in their system due to a long treatment train of engineered barriers and as such relied little on the aquifer. Each of the MAR sites was considered equally effective in removing *Campylobacter* (> 6.0 $\log_{10}$ units) but varied with respect to *Cryptosporidium* and rotavirus based on the differences in aquifer residence and storage times. Tula Valley and Wulpen had the same calculated low $\log_{10}$ removal capabilities where as Parafield and Atlantis had greater calculated treatment capacities due to the longer residence times of water in the subsurface at these sites. Rotavirus removals were the lowest of the three pathogens studied at each site due to their low decay rates (Toze *et al*. 2009).

Case study sites residual risk assessment

The results in DALYs of the risk assessment are reported in Table 4. All results calculated down to 1.0×10^{-10} DALYs per person per year. Tula Valley had the highest residual risk for rotavirus and *Cryptosporidium*. This can be attributed to the lack of pre-treatment and the low residence time of the reclaimed water in the aquifer (20 days average) prior to recovery. Atlantis ~~and~~ had acceptable risk for *Campylobacter*, but higher risk for *Cryptosporidium* and rotavirus. Parafield had low risks for each of the pathogens. Wulpen had a very low risk for each pathogen due to the large pre- and post- recovery treatment trains.

The 95th percentile gives an estimate of the variability of the risk. Where the 95th percentile was below the acceptable risk threshold, the estimate of the risk was considered to be robust. As such the risk assessment from rotavirus for Parafield is not as robust and further work is required to reduce the uncertainty of this risk estimate or further treatment is required to reduce the risk.

Valuing the aquifer barrier in MAR schemes

A sensitivity analysis was performed for each barrier in the treatment train for each case study site and the factor sensitivity (FS) calculated. The FS calculation standardises the comparison between each of the water treatment barriers and the aquifer and thereby aids in valuing the aquifer as part of the larger treatment train. A value of 1.0 indicates a ten-fold increase in risk. Table 5 gives a comparison of the FS values for each of the treatment barriers across the MAR systems.

For Tula Valley most of the FS scores were calculated to be zero as the calculated risk for the removal of a barrier, $N(Barrier)$ was equal to the initial residual risk assessment, $N(Mean)$. For example, the calculated risk for rotavirus was equal to 8.4×10^{-4} DALYs regardless if the chlorination barrier were (WAS)? in place, $N(Barrier) = N(Mean)$. The exception was the aquifer treatment barrier for *Campylobacter* where there was > 6 orders of magnitude increase in risk. For *Campylobacter*, the aquifer was the single most important barrier (compared to chlorination) in determining the residual risk.

For Atlantis the FS analysis indicated that the aquifer was the single most important barrier in determining risk from all pathogens, where again > 6 orders of magnitude increase in risk would result if the aquifer was removed from the treatment train for *Campylobacter*. Like Tula Valley, if the aquifer barrier is in place then the other barriers have little influence in determining the residual risk from *Campylobacter*. For *Cryptosporidium*, the treatment train analysis was more complex with the secondary wastewater treatment plant having almost as large a capacity to reduce residual risk.

For Parafield the aquifer barrier again dominated the risk from *Campylobacter*, resulting in over ten fold increase in risk if it were not present. The aquifer was the third most important barrier with respect to rotavirus and *Cryptosporidium* risk.

For Wulpen the aquifer only played a measurable role in reducing residual risk for rotavirus. The most important barriers were ultrafiltration and reverse osmosis for each of the reference pathogens. Analogously to Tula Valley, the FS value of the aquifer could not be calculated for *Cryptosporidium* and *Campylobacter* as the revised risk in removing the barrier was equal to the initially calculated residual risk, $< 1.0 \times 10^{-10}$ DALYs.

From the FS analysis of Table 5, the subsurface treatment steps were identified as being highly variable in the treatment train in reducing the calculated residual risk. Figure 2 shows the reduction in pathogen numbers of the injectant for each of the reference pathogens at each of the MAR sites. Initial starting pathogen numbers in the water to be recharged for each MAR site is a function of the pre-treatment barriers. Wulpen with its large pre-treatment train (average $\log_{10}$ removals of 14.7, 10.8, 12.4 for rotavirus, *Cryptosporidium* and *Campylobacter* respectively) begin with very low numbers of pathogens in the recharge water. This contrasts with Tula Valley which has no pre-treatment and hence high numbers of pathogens in the recharge water. Atlantis and Parafield sit in between Wulpen and Tula Valley but Parafield has much lower numbers of pathogens than Atlantis as its recharge water was urban stormwater as opposed to reclaimed effluent. The pathogen numbers for each site steadily decrease as a function of the decay rate and the residence time in the aquifer reported in Table 2.

Figure 3 shows the dose-response curves (WHO 2004; EPHC-NHMRC-NRMMC 2008a) used to calculate the probability of infection from a given dose of pathogens. The probability of infection is then multiplied by the DALYs per infection to calculate the final residual risk of each MAR system in Table 4. The infection dose-response curve results in a conversion of the risk of infection to DALYs and is responsible for the shapes of the resultant curves plotted in Figures 4 and 5. These figures show the DALYs per person per year for each of the MAR schemes as a function of aquifer residence time and pathogen decay rates. It is important to note that the decay rates are assumed to be linear and unchanging as a function of time. This investigates the treatment role of the aquifer by plotting DALY’s as a function of mean residence time. The change in DALYs from *Campylobacter* as a function of aquifer residence time is not shown as the risks from *Campylobacter* were not quantifiable for all sites. Wulpen is not shown in Figures 4 and 5 as the calculated risk was $< 1.0 \times 10^{-10}$ annualised DALYs for each of the reference pathogens.

Figure 4 shows the change in DALYs from rotavirus as a function of aquifer residence time for Tula Valley, Parafield and Atlantis. For Tula Valley and Atlantis the risks from rotavirus are high.

Figure 5 shows the change in DALYs from *Cryptosporidium* as a function of aquifer residence time for Tula Valley, Parafield and Atlantis. Parafield and Atlantis reach the value of 1×10^{-6} DALYs within the actual ranges of the residence times for the case study sites. Tula Valley risks remain higher than other sites.
I think this is the most important section and we need to highlight it more?

Discussion

Characterisation of the value of aquifer treatment

In order to provide safe drinking water with MAR an integrated approach to managing risks needs to be adopted which includes characterisation of the aquifer treatment barrier. To date there have been no reported case studies where the aquifer treatment barrier of a MAR scheme is accredited with $\log_{10}$ removals for pathogens much like in conventional drinking water treatment. In valuing the treatment capacity, integrity and independence of aquifers, MAR can be brought to the same level as conventional engineered water treatment in an integrated water supply system.

The value of the aquifer barrier was determined by the relative $\log_{10}$ removal characteristics with respect to the reference pathogens (Table 3). The $\log_{10}$ removals for *Campylobacter* are > 6.0 $\log_{10}$, a similar value attributed to other water treatment technologies such as reverse osmosis (NRMMC-EPHC 2006). For *Cryptosporidium* the value of the aquifer was similar to primary treatment for Tula Valley and Wulpen, ultra filtration for Atlantis and dual media filtration with coagulation at Parafield depending upon residence time of the recharge water in the aquifer. Rotavirus had the poorest $\log_{10}$ removals in the aquifer (Table 3) due to the very low decay rates (Table 2). See previous comment

Knowledge of both the aquifer residence time and the rate of decay is essential for enabling the treatment value of the aquifer to be determined (Table 3). The decay of pathogens in groundwater during MAR is influenced by a range of factors such as the activity of indigenous ground water microorganisms, temperature, oxygen concentrations and organic carbon concentrations (Gordon and Toze 2003, Toze *et al.* 2004). Research has shown that bacteria tend to survive for much shorter times in aquifers than enteric viruses and protozoa (Toze *et al.* 2004) but the relative times can be aquifer-dependent. Another issue relating to decay is that decay is not always linear. The decay of some pathogens, in particular the more resistant viruses have been observed to have changes in slower decay rate with time. Thus, in these cases a broken stick model of decay with different rates of decay may be more appropriate than a single rate of decay.

Risk assessment for the case study sites

To evaluate the risk from enteric pathogens during MAR the potential presence of these pathogens and their numbers need to be determined. The major source of all enteric pathogens is faecal contamination, particularly from human faecal material. The largest number of enteric pathogens can be expected to be detected in untreated wastewater (Table 2) with numbers reducing through treatment processes (Table 3). The potential presence of enteric pathogens in the recharge water (Figure 2) is directly linked to the potential of human faecal matter contaminating the water. Thus, in this study, the pathogen risk for Wulpen was assessed to be very low due to the high level of treatment prior to MAR. Conversely, Tula Valley had the highest risk, due to a low level of engineered treatment which is reflected in the QMRA results (Table 4). The Atlantis scheme has less opportunity for the presence of microbial pathogens due to the blending of treated wastewater and stormwater, while the risk in the Parafield system is more limited to the potential for sewer pump-station overflows and contamination from animal faeces.

An accurate risk assessment also requires the input of accurate pathogen numbers. The initial pathogen numbers in the recharge water (Figure 2) are influenced by a range of factors such as disease burden of the local population and the level of treatment for the recharge water. The numbers of some pathogens is also less accurate due to the difficulties in detection. For example, the detection of *Cryptosporidium* oocysts and rotavirus is difficult due to the lack of suitable culture methods and the low numbers (≤ 100 units) usually present in large volumes of water (>1 L)?. Numbers in river, canal and recreation water for *Cryptosporidium* oocysts have been quoted as between 5 and 240 oocysts per 10 litres (Schets *et al.* 2008, Plutzer *et al.* 2008, Mons *et al.* 2009). In comparison rotavirus numbers in similar water types have been reported to be between 2 and 200 detectable units per litre (Mehnert *et al.* 1993, Lodder *et al.* 2005).

In general the risks evaluated for each of the MAR sites (Table 4) were in the order Tula Valley > Atlantis > Parafield > Wulpen for *Cryptosporidium* and rotavirus but all had low risks for the bacterial pathogen, *Campylobacter*. Only Wulpen and Parafield met the mean WHO guideline for all the reference pathogens (Table 4). The health effects caused by the wastewater irrigation at the highest risk site, Tula Valley include a 16 fold increase in morbidity by helminths in children appear to support this result (Blumenthal *et al.* 1991; Blumenthal *et al.* 2001). Human health impacts have not been evaluated at the other case study sites.

Standardisation of determining aquifer treatment

The factor sensitivity (FS) analysis method (Zwietering and van Gerwen 2000; Smeets *et al.* 2006) was used to give an indication of the relative value of the aquifer (in terms of reducing human health risk) vis-à-vis the other barriers within the treatment train for each case study site. For the Tula Valley system (for *Campylobacter*) this was the maximum risk possible (4.6×10^{-3} reduced to $< 1 \times 10^{-10}$ DALYs) about a million-fold reduction. Conversely for Wulpen the aquifer treatment effect was not measurable as the risk from *Campylobacter* was already $< 1 \times 10^{-10}$ DALYs (Table 5), resulting in the observed FS ratio of 0.00. At Wulpen there are multiple barriers that are effective in reducing the risk to an acceptable level and even if any one barrier fails the risk remains negligible. The Tula Valley site demonstrates the high value placed on the aquifer for mitigating the risk from pathogenic bacteria, it is the only barrier that significantly affects risk for *Campylobacter*. Similarly, for the Atlantis and Parafield sites if the aquifer barrier is in place then the risks from pathogenic bacteria are negligible.

For Tula Valley the role of the aquifer is not measureable for *Cryptosporidium* as the risk with removal of a barrier, *N(Barrier)* is the same as the residual risk (*N(Mean)* i.e. the maximum possible risk of 1.5×10^{-3} DALYs, Table 4). This contrasts to Atlantis where the aquifer is the single most important barrier (highest FS scores) influencing risk for each of the reference pathogens. For Parafield the aquifer has the highest value in reducing risk for *Cryptosporidium* and *Campylobacter*, but post-recovery UV and chlorine disinfection was each superior to the aquifer in reducing risk for rotavirus. For Wulpen the aquifer has little risk reduction value, most important are the ultrafiltration and reverse osmosis treatment barriers.

Integrating aquifer treatment with engineered treatments

To date aquifer treatment has been slow to integrate into an engineered water treatment train due to the difficulty in measuring a quantifiable reduction in risk. This is in part due to the adoption of risk-based management systems, such as the Hazard Analysis and Critical Control Point (HACCP) approach. HACCP concepts have been adopted by the water industry and promoted as a more proactive approach to managing drinking water supplies (WHO 2004; EPHC-NHMRC-NRMMC 2008a), as well as recycled water systems (NRMMC-EPHC 2006) and even MAR systems (EPHC-NHMRC-NRMMC 2008c). Yet, aquifer treatment remain difficult to integrate as there are no easily identifiable critical limits and control points such as for the more common water treatment technologies such as chlorination which uses contact time, UV disinfection which uses UV-transmittance and membrane treatments which use pressure and electrical conductivity.

It is proposed that an extension of the FS sensitivity analysis could also be used to provide a means of generating evidence-based critical limits to manage critical control points. While there are no health-based targets for pathogen numbers (Figure 2) QMRA can be used to address the setting of critical limits. This is done by treating the DALYs estimates as representing acceptable estimates of “absolute” risk and comparing them to the agreed international human health risk benchmarks, 1.0×10^{-6} DALYs (WHO 2004). In this instance, the comparison of the Parafield risk estimate indicated that the residual risk was acceptable for *Campylobacter* when compared to this benchmark and this conclusion was robust as indicated by the 95th percentile being less than the benchmark value. However, for rotavirus the assessment was less robust and the required aquifer residence time was just great enough for the scheme to support so additional post-recovery treatment could be required. An illustrative example for setting of critical limits for mean aquifer residence time comes from the *Cryptosporidium* for the Atlantis site, where the mean residence time needs to exceed ~550 days to achieve tolerable levels of risk. Again, this assumes that the pathogen decay rates of Toze *et al*. (2009) are linear and are representative of the processes occurring in the subsurface of this site. Use of the residence time critical limit could also be used to design infiltration and extraction pumping regimes to ensure the mean residence time in the aquifer is achieved. Where it is not already accurately know, such as in the Atlantis and Tula Valley examples, the aquifer residence time can be determined by use of suitable groundwater tracers. This can include both applied tracers, substances injected into the groundwater intentionally and thereby in controlled doses, time intervals and locations (such as SF_6) or natural tracers (such as the recharge water electrical conductivity) if this has marked temporal variation. Knowledge of the residence time in the aquifer coupled with pathogen decay rates could then be used to fully appreciate the water treatment function of the subsurface and integrate the aquifer barrier with the engineered treatments in the provision of safe drinking water.

Conclusions

For the four MAR case study sites considered, the QMRA provides a means of quantifying the combined effects of aquifers and engineered treatments for reference pathogens in terms of $\log_{10}$ removal characteristics. For each site the aquifer had > 6 $\log_{10}$ removal predicted for *Campylobacter* whilst rotavirus and *Cryptosporidium* had more variable removal rates depending upon the residence time in the aquifer. The use of QMRA was found to be useful tool in establishing the value of the aquifer within the treatment train and allowed the assessment of human health risk from pathogens in terms of DALYs. A sensitivity analysis was used to assess which of the treatment barriers was most important in each of the MAR systems. This allowed the integration of the aquifer treatment characteristics into the larger engineered treatment train and could be used in the future to quantitatively assess the reduction of human health risk for MAR systems more generally.

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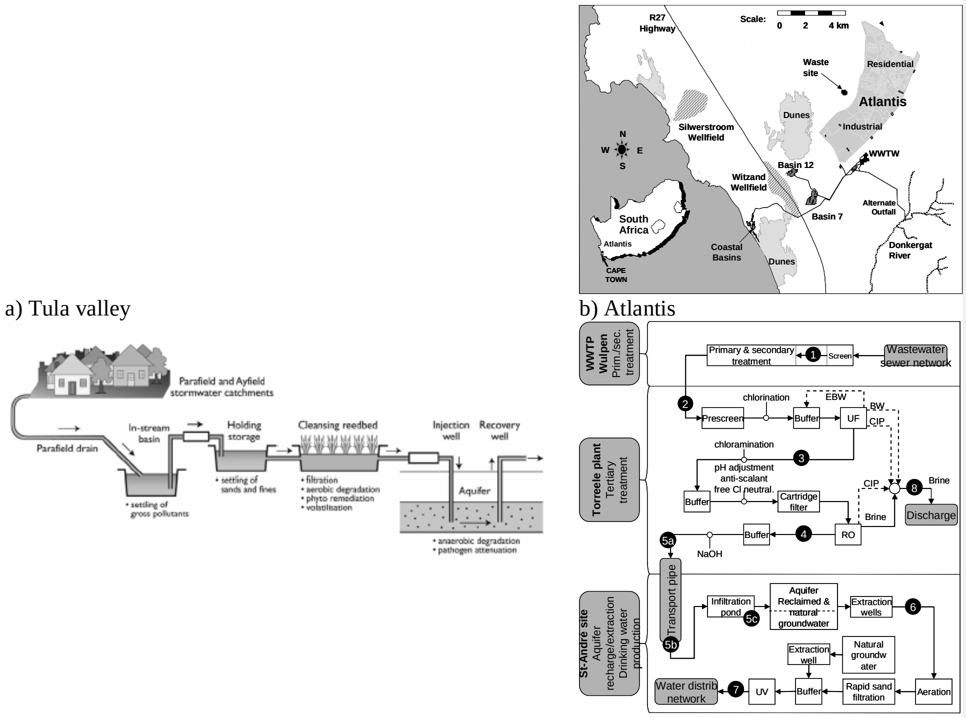

a) Tula valley

b) Atlantis

c) Parafield

d) Wulpen

Figure 1. Case study site system diagrams

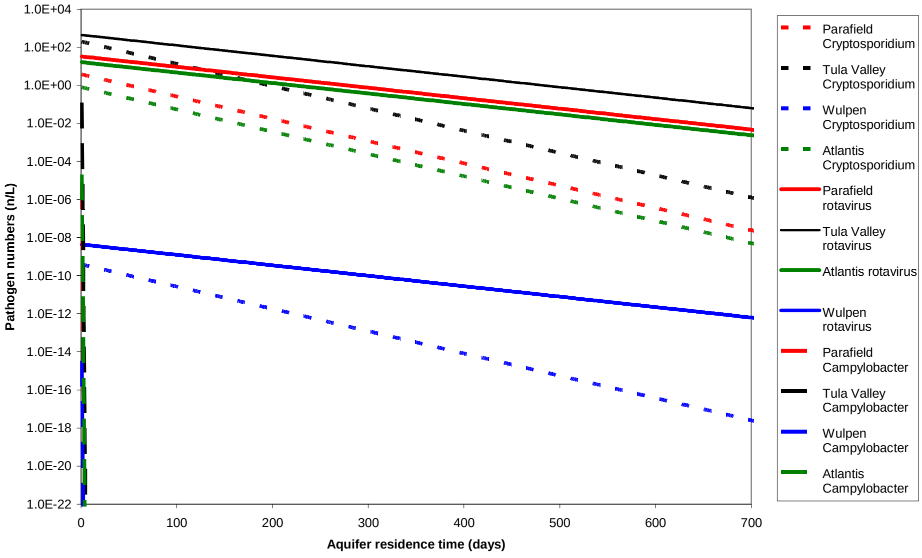

Figure 2. Decay in pathogen numbers as a function of residence time

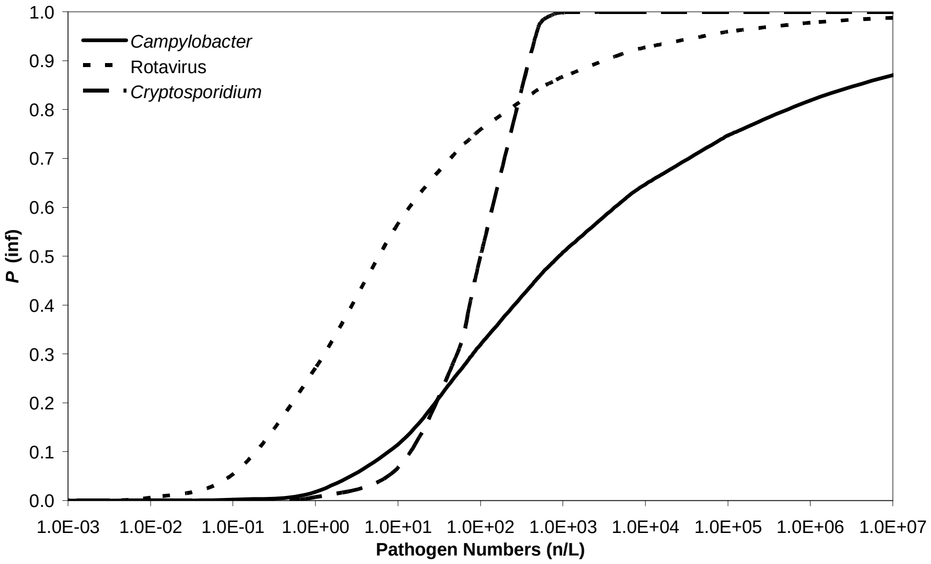

Figure 3. Standard dose-response curves used in this study (WHO 2004; NRMMC-EPHC 2006)

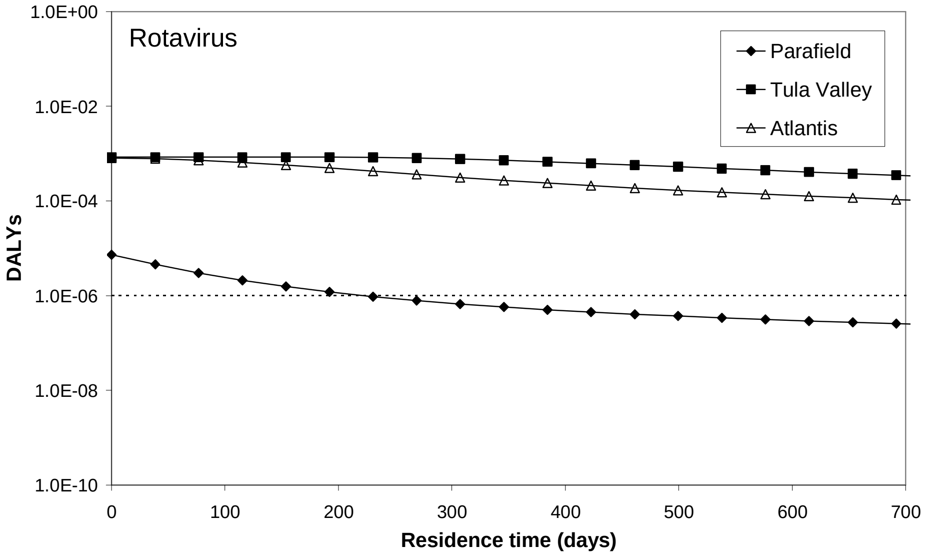

Figure 4. Changes in mean DALYs from rotavirus with increasing residence times in the aquifer

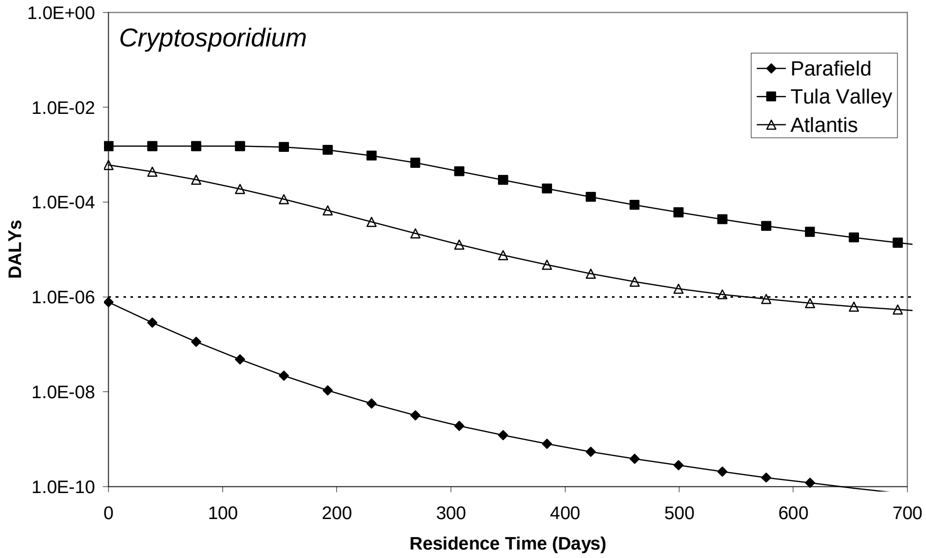

Figure 5. Changes in mean DALYs from *Cryptosporidium* with increasing residence times in the aquifer

Table 1. Description of case study sites

General information	**Tula Valley, Mexico**	**Atlantis, South Africa**	**Parafield, Australia**	**Wulpen, Belgium**
Town population	72,500 (Cerro Colorado region)	250,000	122,000 (Salisbury region)	60,000
Mean Annual Rainfall (mm)/Mean annual evaporation	550	450	450	830
Source water	Reclaimed effluent	Reclaimed domestic effluent / Stormwater	Stormwater	Reclaimed effluent
Mean Temp of Source water (°C)	21	21	18	20
Redox status of recharge water	-47—37mV	1-10mV and up to 300mV in 2nd well field	Aerobic	Aerobic
Year of recharge commencement	1986	1976	2006	2002
Annual Recharge Volume (m^3/year)	>788 x 10^6 for the Tula Region	Stormwater: 1.5 – 2.5 x 10^6 I have 2169cubes per day in summer to 72000 as peak flow in winter Reclaimed water: 5x 10^6	0.25 x 10^6	1.8 x 10^4
Annual Extraction Volume (m^3 / year)	12.6 x10^6 (Cerro Colorado region)	4.6 x 10^6	0.25 x 10^6	3.5 x 10^6
Average aquifer residence time (days)	20	365	268	35
Minimum flow path length (days)	Unknown	182	100	35
Mean temperature of Aquifer (°C)	30	20	23	12
Redox status of aquifer	Iron reducing	Nitrate reducing	Nitrate reducing	Nitrate reducing
% recharged water recovered from aquifer	100	40	90	70
MAR system components				
1. Capture Zone	Reclaimed effluent	Residential stormwater catchment and reclaimed effluent	Residential stormwater catchment	Reclaimed effluent
2. Pre-treatment	Primary sedimentation	Activated sludge, maturation ponds, constructed wetland	Constructed reedbed	Activated sludge, ultrafiltration, reverse osmosis, UV disinfection
3. Recharge	Infiltration from storage canals and reservoirs and irrigation areas	Recharge basins	Recharge wells	Recharge basins
4. Subsurface storage	Partially confined basaltic aquifer with some volcanic ash and lava intervals	Unconfined sandy aquifer	Confined lime stone aquifer	Unconfined sandy aquifer
5. Recovery	Spring discharge	Extraction wells	Extraction wells	Extraction wells
6. Post-treatment	Chlorination	Softening, chlorination	Aeration tank, Chlorination, UV disinfection	Aeration, rapid sand filtration, UV disinfection
7. End use	Drinking water	Drinking water	Drinking water	Drinking water

Comment [W2]: Please check all the numbers in this column as being accurate

Comment [BG3]: edited

Table 2 Probability distribution functions used for the quantitative risk assessment

Barrier	**Atlantis** LOOK at the table below for my inputs from Analytica			**Parafield**		
Pathogen	Rotavirus	*Cryptosporidium*	*Campylobacter*	Rotavirus	*Cryptosporidium*	*Campylobacter*
Pathogen source water number††	0.3, 0.6 * / 443, 220**	0.5, 1.2 * / 200, 100***	3.9, 9.8 * / 10^1-10^4 *	0.3, 0.6*	0.5, 1.2*	3.9, 9.8*
Artificial wetland‡	0.0, 0.0 ,0.0	0.5, 0.5, 1.0	1.5,2,2.5	0.0, 0.0, 0.0	0.5, 0.5, 1.0	1.5, 2.0, 2.5
WWTP‡	0.2,1.7,2.3	0.4, 1.8, 3.8	0.6, 1.4, 3.7			
UF‡						
RO‡						
UV‡						
Subsurface storage (residence time days)		182 ,365, 730			241, 58††	
Pathogen decay rate 1-log (days)***	0.0055, 0.0036	0.012, 0.0030	5.6†	0.0055, 0.0036	0.012, 0.0030	5.6†
Recovery (% mixing)		0.4			0.9	
Rapid sand‡ filtration‡						
UV‡				2.0, 2.0, 3.0	2.0, 3.0, 4.0	2.0, 3.0, 4.0
Chlorination‡	1.0, 2.0, 3.0	0.0 ,0.0 ,0.5	2.0, 4.0, 6.0	1.0, 2.0, 3.0	0.0, 0.0, 0.5	2.0, 4.0, 6.0
Barrier	**Wulpen**			**Tula Valley**		
Pathogen	Rotavirus	*Cryptosporidium*	*Campylobacter*	Rotavirus	*Cryptosporidium*	*Campylobacter*
Pathogen source water number††	6.8, 45,662	200, 100*	10^1-10^4	443, 220**	200, 100*	10^1-10^4
Artificial wetland‡						
WWTP‡	0.2, 1.7, 2.3	0.4, 1.8, 3.8	0.6, 1.4, 3.7			
UF‡	4.0, 4.0, 6.5	3.0, 3.0, 7.0	4.0, 4.0, 7.0			
RO‡	2.7, 3.0, 6.5	3.0, 3.0, 7.0	4.0, 4.0, 7.0			
UV‡	2.0, 2.0, 3.0	2.0, 3.0, 4.0	2.0, 3.0, 4.0			
Subsurface storage (residence time days)		35, 35, 40			20, 40	
Pathogen decay rate 1-log (days)***	0.0055, 0.0036	0.012, 0.0030	5.6†	0.0055, 0.0036	0.012, 0.0030	5.6†
Recovery (% mixing)		0.7			1	
Rapid sand‡ filtration‡	0.1,0.5,3.9	0.8, 2.9, 5.4	0.8,1.5,3.3			
UV‡		2.0, 3.0, 4.0	2,3,4			
Chlorination‡	1,2,3			1.0, 2.0, 3.0	0.0, 0.0, 0.5	2.0, 4.0, 6.0

Engineered treatment efficacy $\log_{10}$ removal efficiencies come from Smeets *et al*. (2006);EPHC–NHMRC–NRMMC (2008b); except Wulpen from Ayuso-Gabella *et al*. (2007)

* 95th Percentile as per Table A3.1 of the Draft Guidelines for Stormwater Harvesting and Reuse: *Campylobacter* 15 n/L; *Cryptosporidium* 1.8 n/L; rotavirus 1 n/L (NRMMC-EPHC 2008b).

** Robertson *et al* (2006)

***cited in Kocwa-Haluch and Zalewska (2002)

****Toze *et al*. (2009), normal distribution, mean, standard deviation

† single value only

†† lognormal distribution mean, standard deviation

‡ triangular distributions: minimum, most likely, maximum

Effluent_concentration using Analytica as described in del 6.2 post reed bed – ie- conc going into the recharge basin		
Reference_pathogens	Salmonella	
	Peak storm flow	Summer base flow
Min	1.04E-02	2.56E-02
Median	9.28E+00	1.00E+01
Mean	8.03E+02	4.79E+02
Max	1.77E+05	2.81E+04
Std. Dev.	6.92E+03	1.95E+03
	Rotavirus	
	Peak storm flow	Summer base flow
Min	1.95E+03	6.85E+03
Median	5.30E+05	1.15E+06
Mean	5.20E+06	5.25E+06
Max	1.14E+09	1.19E+08
Std. Dev.	3.98E+07	1.16E+07
	Cryptosporidium	
	Peak storm flow	Summer base flow
Min	4.05E+03	1.92E+01
Median	1.23E+05	5.87E+02
Mean	4.38E+05	2.08E+03
Max	8.77E+06	4.17E+04
Std. Dev.	8.20E+05	3.90E+03
	Giardia	
	Peak storm flow	Summer base flow
Min	1.51E+03	7.10E+00
Median	1.40E+04	6.60E+01
Mean	2.14E+04	1.01E+02
Max	1.30E+05	6.14E+02
Std. Dev.	2.12E+04	9.99E+01

Table 3 Calculated aquifer barrier removal efficiency in $\log_{10}$ units

Pathogen		Tula Valley		Atlantis		Parafield		Wulpen	
		Aquifer	Non-aquifer	Aquifer	Non-aquifer	Aquifer	Non-aquifer	Aquifer	Non-aquifer
Rotavirus	Min	0.0	1.0	0.0	1.2	0.0	3.0	0.0	8.3
	Most likely	0.2	2.0	2.5	3.7	1.4	4.0	0.2	17.2
	Max	0.8	3.0	> 6.0	5.3	> 6.0	6.0	0.7	25.2
Cryptosporidium	Min	0.0	0.0	0.3	0.9	0.1	2.5	0.0	11.2
	Most likely	0.4	0.0	5.0	2.3	2.8	3.5	0.4	16.7
	Max	0.9	0.5	> 6.0	5.3	> 6.0	5.5	0.9	31.2
Campylobacter	Min	> 6.0	2.0	> 6.0	4.1	> 6.0	5.5	> 6.0	13.4
	Most likely	> 6.0	4.0	> 6.0	7.4	> 6.0	9.0	> 6.0	16.9
	Max	> 6.0	6.0	> 6.0	12.2	> 6.0	12.5	> 6.0	29.0

Table 4 Mean, Median and 95th percentile residual risk assessment in DALYs

Pathogen		Tula Valley	Atlantis	Parafield	Wulpen
Cryptosporidium	Mean	**1.5×10^{-3}**	**7.0×10^{-6}**	7.7×10^{-9}	$< 1.0 \times 10^{-10}$
	Median	**1.5×10^{-3}**	5.3×10^{-9}	2.0×10^{-10}	$< 1.0 \times 10^{-10}$
	95th	**1.5×10^{-3}**	**1.2×10^{-5}**	1.8×10^{-8}	$< 1.0 \times 10^{-10}$
Rotavirus	Mean	**8.4×10^{-4}**	**2.3×10^{-4}**	8.5×10^{-7}	$< 1.0 \times 10^{-10}$
	Median	**8.4×10^{-4}**	**4.9×10^{-5}**	5.0×10^{-8}	$< 1.0 \times 10^{-10}$
	95th	**8.4×10^{-4}**	**8.3×10^{-4}**	**3.1×10^{-6}**	$< 1.0 \times 10^{-10}$
Campylobacter	Mean	$< 1.0 \times 10^{-10}$	$< 1.0 \times 10^{-10}$	$< 1.0 \times 10^{-10}$	$< 1.0 \times 10^{-10}$
	Median	$< 1.0 \times 10^{-10}$	$< 1.0 \times 10^{-10}$	$< 1.0 \times 10^{-10}$	$< 1.0 \times 10^{-10}$
	95th	$< 1.0 \times 10^{-10}$	$< 1.0 \times 10^{-10}$	$< 1.0 \times 10^{-10}$	$< 1.0 \times 10^{-10}$

Table 5 Factor Sensitivity ratio – relative importance of barriers

	Tula valley	Atlantis	Parafield	Wulpen
Rotavirus				
Constructed wetland	-	0.00†	0.00†	-
Secondary treatment	-	0.35	-	1.14
Ultra filtration	-	-	-	4.51
Reverse osmosis	-	-	-	3.49
UV disinfection	-	-	-	2.69
Aquifer	0.00*	0.55	0.94	2.23
Rapid sand filtration	-	-	-	0.92
UV disinfection	-	-	1.94	2.23
Chlorination	0.00*	0.43	1.66	-
Cryptosporidium				
Constructed wetland	-	0.78	0.61	-
Secondary treatment	-	1.65	-	1.24
Ultra Filtration	-	-	-	3.48
Reverse Osmosis	-	-	-	3.48
UV disinfection	-	-	-	2.57
Aquifer	0.00*	1.93	2.03	0.00*
Rapid sand filtration	-	-	-	1.92
UV	-	-	2.78	2.57
Chlorination	0.00*	0.05	0.14	-
Campylobacter				
Constructed wetland	-	0.00*	0.00*	-
Secondary treatment	-	0.00*	-	0.00*
Ultra filtration	-	-	-	0.00*
Reverse osmosis	-	-	-	0.00*
UV disinfection	-	-	-	0.00*
Aquifer	6.66	7.57	1.29	0.00*
Rapid sand filtration	-	-	-	0.00*
UV disinfection	-	-	0.00*	0.00*
Chlorination	0.00*	0.00*	0.00*	-

† removal of viruses by constructed wetlands is considered to be negligible (NRMMC-EPHC 2006).

* FS score could not be calculated as the resultant risk was equal to the residual risk.