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CSIRO

Determining Requirements for Managed Aquifer Recharge in Western Australia

Final Report
Water Foundation Project No. 022/04G

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The University of Western Australia

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The Water for a Healthy Country Flagship aims to provide Australia with solutions for water resource management, creating economic gains of $3 billion per annum by 2030, while protecting or restoring our major water ecosystems. The work contained in this report is collaboration between CSIRO, Water Corporation WA, ChemCentre, Curtin University and The University of Western Australia.

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Cover Photograph: Construction of infiltration galleries using the Atlantis Leach System® at the Floreat site.

Photographer: Simon Toze

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FOREWORD

Scientific modelling is telling us that we can expect changing patterns and further declines in rainfall in Western Australia's south-west.

While the volume of surface water in our dams continues to decline, Perth is fortunate in having vast underground aquifers which, if managed well, can sustain our water future.

The solution is quite clear.

As WA's population continues to increase, along with water use, we will have to make better and much wiser use of our available water resources – including finding every way possible to recycle and re-use what we can.

Above all, we must harness the best science and be innovative in both science and in our policy research and decisions.

This Managed Aquifer Recharge project exemplifies those approaches.

A sustainable water future for Western Australia will be realised only if governments at all levels, our scientific community and all water users are committed to cooperative action.

This three-year project is a fine example of that commitment and cooperation, with research carried out by the CSIRO, the Water Cooperation, ChemCentre, Curtin University and the University of Western Australia.

The project was made possible by funding from the WA Government Water Foundation, CSIRO Water for a Healthy Country Flagship and the Water Cooperation of Western Australia.

The results have identified the best methods for infiltrating aquifers; the behaviour and persistence of trace organic compounds under recharge scenarios, public attitudes and the degree of community support for aquifer recharge; and assessed the human health risks of using recycled water via MAR for irrigation.

I congratulate all researchers and the authors of this report on their diligence and the quality of their work. They have shown that Perth's urban water supply can benefit from managed aquifer recharge of recycled water, providing we employ the best design and the best science.

Given the quality of our scientific, engineering and policy communities, I am confident we can succeed.

Kim Taylor

Director General

Department of Water

EXECUTIVE SUMMARY

Managed Aquifer Recharge (MAR) is a technique that has great potential for assisting the uptake of water recycling in Western Australia, particularly in the south-west on the Swan Coastal Plain. There is strong potential for MAR to have a major impact on levels of water recycling in urban environments. To further determine the applicability of MAR in urban environments a research project was funded through the Western Australian Water Foundation, CSIRO Water for a Healthy Country Flagship, and the Water Corporation WA. The project was divided into four linked Work Packages to cover the major issues that had been initially identified as relating to MAR in Western Australia. The first and major component focused on the issues relating to setting up and operating a MAR scheme. The second investigated in detail the persistence of trace organics in groundwater using laboratory column experiments. The third examined social attitudes to water recycling, in particular those relating to MAR. The fourth component examined the exposure risks from pathogens and trace organics in water recovered from MAR schemes.

Design and Operation of Infiltration Galleries and Water Quality Changes

The research in this work package focused on investigating the ability to recharge treated wastewater to the superficial aquifer using infiltration galleries and the movement of the recharged water through the aquifer; assessing changes in the quality of the recharged water during its residence in the aquifer; and identifying any management and operational issues that might be encountered in operating such a MAR scheme. While there are a range of MAR methods and types of source water, it was decided that infiltration galleries using secondary treated wastewater was the most appropriate method to test for the current project. Infiltration galleries have the advantage of being cheaper, less sophisticated to operate and are potentially less prone to clogging than well injection systems. Infiltration galleries also have potential advantages over MAR systems that use ponds (such as pond infiltration and soil aquifer treatment methods) in that they are located below ground and thus do not take up the valuable ground area that pond systems would. There is also considerably less potential for unsupervised access to the recharging water by the community, domestic animals or wildlife. In addition, the lack of exposed water means that there is no chance for mosquito breeding in the ponded water prior to recharge.

The research outcomes demonstrated that treated wastewater can be efficiently and sustainably recharged to the superficial aquifer in urban areas on the Swan Coastal Plain using infiltration galleries. Due to clogging, the use of gravel-filled trenches was not as effective or sustainable as the Atlantis Leach System® for infiltrating large quantities of secondary treated wastewater. A short-term experiment involving an increase in the inflow rate to the gallery constructed using the Atlantis Leach System® revealed no evidence of clogging with an accelerated average inflow rate of 60 L/min.

Using a three-dimensional MODFLOW-MODPATH simulation, an estimation of the minimum residence time in the saturated zone at the Floreat Infiltration Galleries site was determined to be approximately 70 days between the galleries and the extraction bore. Based on a conservative transport model calibrated with chloride data, the estimated maximum dilution with background groundwater was 80% at the extraction bore, with a pumping rate of 250 KL/day (i.e. the recovered water consisted of 20% recharged water/80% groundwater). Investigations using two different tracers demonstrated that the recharged water took about 3 days to travel through 7m (70%) of the thickness of the unsaturated zone.

A comprehensive investigation of water quality during recharge and movement through the aquifer indicated that changes occurred for most of the tested analytes in the recharge water. Using in-situ diffusion chambers, selected enteric microorganisms (*Cryptosporidium*, adenovirus, rotavirus, coxsackievirus, MS2, *E. coli, S. enterica* and *E. faecalis*) were used to demonstrate that the aquifer had an active treatment capacity to remove pathogens. In addition to this, extensive sampling of the recharged water/groundwater from monitoring bores along the transect of the MAR scheme showed that enteric viruses and bacteriophage were not detected in the aquifer further than 1 metre from the infiltration galleries. Some periodic detection of thermotolerant coliforms and enterococci in water collected from various monitoring bores occurred but based on the studied decay rates of these microorganisms it was considered that this is an artefact of the infiltration galleries being located on a sheep paddock and these microorganisms being sourced via surface contamination from sheep faeces, not from the recharged wastewater.

Removal of nutrients and trace organics during passage through the unsaturated zone was assessed by comparing the concentrations in the treated wastewater entering the infiltration galleries with water sampled from monitoring bores located around the galleries. Significant declines in phosphate were observed within a few metres of the infiltration galleries. There was no evidence of attenuation or removal of nitrate due to the aerobic nature of the aquifer preventing denitrification from occurring. Analysis for the presence of trace organic chemicals in the recharged water focused mostly on the diazepam group of pharmaceuticals (carbamazepine, oxazepam, diazepam and temazapam). The concentrations of carbamazepine and oxazepam, and to a lesser extent temazepam, were observed to reduce in monitoring bores down-gradient from the recharge source. Based on mass recovery rates, a field assessment of carbamazepine revealed no degradation of this compound. Using the ratio of oxazepam to the conservative carbamazepine, it was determined that there was no evidence to suggest that biodegradation of oxazepam was occurring, although due to dilution, the measured oxazepam concentrations were below detection levels in the recovered water.

The assessment of operational and management requirements of MAR schemes, such as infiltration galleries, using treated wastewater as a source water identified a number of issues for consideration. It was shown that the Atlantis Leach System® gave a superior performance to the use of gravel in the construction and operation of the infiltration galleries. The gravel-filled gallery operated well for several months and then showed signs of clogging which eventually resulted in this gallery being shut down and replaced with the Atlantis Leach System®. These results indicated that care is needed in the original design of MAR systems, with the preliminary testing of any previously untested systems and designs being strongly recommended. Ongoing monitoring of the performance of the infiltration gallery system determined that monitoring various parameters and analytes and undertaking targeted hydrogeological experiments were invaluable in gaining a better understanding of the movement of the water through the unsaturated zone and the aquifer. The results obtained were able to be used to model the movement of the recycled water through the MAR scheme. The modelling was able to predict the residence time within the aquifer but the level of heterogeneity within the aquifer and the highly transmissive nature of the aquifer meant that an absolute understanding of the transport and residence of the water within the aquifer is still required.

Other issues relating to the operation and management of infiltration gallery MAR schemes were also observed and lessons were learnt from the occurrence of these matters. Issues related to factors such as the initial design and set up of the MAR schemes; the reliability of the supply and the influence this may have on the day-to-day operation of the MAR scheme;

the influence of dissolved iron on the quality of the recovered water; the appropriate instalment and protection of the pipe system delivering the treated wastewater to the infiltration galleries; the clogging potential of the infiltration galleries and the associated appropriate monitoring techniques; and the appropriateness of the equipment used to monitor the operation of the MAR schemes.

Fate of Trace Organics Using Laboratory Column Experiments

The presence of trace organics in the water used as a source for recharge and their behaviour and fate in the aquifer had been identified at the commencement of the project as a major area where data was limited. The second work package was therefore designed to study the potential persistence of a range of trace organics under different conditions expected to occur in the different aquifers on the Swan Coastal Plain.

The fate of specific trace organic compounds was investigated under laboratory conditions in large-scale columns. Experiments were conducted over a 12-month period using different aquifer sediments, redox conditions and types of recharge water. The experiments were designed to simulate (i) a deep injection MAR option involving the injection of tertiary reverse osmosis treated recycled water into the anaerobic Leederville aquifer, and (ii) a shallow injection MAR option involving the injection of secondary treated recycled water into the aerobic Tamala aquifer containing Spearwood sediment. The shallow injection MAR option experiment was undertaken to provide comparable in-lab data to the Floreat Infiltration Gallery (FIG) field study. The nine trace organic compounds used in the research were bisphenol A (BPA), 17β-estradiol (E2), 17α-ethynylestradiol (EE2), oxazepam (OXAZ), carbamazepine (CARB), N-nitrosodimethylamine (NDMA), N-nitrosomorpholine (NMOR), iohexol (IOX) and iodipamide (IDP).

The behaviour and persistence of each trace organic under the different redox conditions and water types in the Leederville and Spearwood sediments were assessed based on their chemical retardation coefficient (R) and degradation half-life, determined from the experimental data.

In the Spearwood sediment, which has a low organic carbon content, none of the trace organics were retarded, indicating that these compounds would travel at near groundwater velocities in the Tamala aquifer. Degradation of E2, EE2, BPA and IOX was observed, however the other trace organics tested were not degraded. Therefore, concentrations of the nitrosamines (NDMA and NMOR), pharmaceuticals (OXAZ and CARB), and the x-ray contrast medium (IDP) were determined unlikely to be substantially reduced during MAR under these aquifer conditions.

In contrast, in the relatively high organic carbon content Leederville sediment, all the trace organics tested except the nitrosamines and IOX showed substantial sorption to the aquifer material. This suggests that these trace organics would have slow migration rates in the Leederville aquifer. Rapid degradation of E2, EE2, BPA and IDP were observed in the columns containing the Leederville aquifer material, however, none of the other trace organics were degraded. Therefore, concentrations of the nitrosamines, pharmaceuticals, and IOX are unlikely to be reduced substantially during aquifer passage associated with MAR in the Leederville aquifer.

Geochemical changes as a result of the injection of aerobic reverse osmosis (RO) treated water into the reduced Leederville sediment were also observed. These changes included rapid oxygen consumption with the production of sulphate (suggesting pyrite oxidation); and increases in selected anions and cations, suggesting mineral dissolution of possibly gypsum, dolomite and ankerite. Despite these observed geochemical reactions, however, no increase in the concentration of heavy metal(loids) in the column water was observed.

As determined in Work Package 1, nitrate is persistent in the superficial aquifer due to the aerobic nature of the aquifer. Experiments were thus undertaken in the large-scale columns to investigate the potential for inducing denitrification within the recharge zone of MAR schemes to remove the nitrate from the recharged water. These experiments demonstrated that removal of nitrate from the recharged water was possible during aquifer passage through the use of ethanol carbon-dosing. Using this technique, denitrification half-lives of 1.9 days were observed within the columns. An additional benefit of inducing denitrifying conditions using the ethanol dosing method was that the reducing conditions resulted in enhanced degradation of iodipamide (IDP).

Community Attitude and Behaviour Research

At the commencement of the research project it was identified that very little was known about the social acceptability of recycling water via MAR. As a result, a three-year investigation was undertaken into its social acceptance. This research explored community perceptions, attitudes and intended behaviour towards MAR for a range of fit-for-purpose uses. The research was undertaken via a behavioural modelling survey of 500 Perth householders. While the research encompassed assessing people’s attitudes and intended behaviour to a range of fit for purpose uses, much of the investigation eventually focused on indirect potable reuse as this was considered to be potentially the least acceptable and was thus used as the end benchmark for community acceptance for MAR.

The results obtained from the survey found that, while over half of respondents intended to support a MAR scheme in Perth, a significant proportion of these (one-fifth) were not forming strong convictions about the scheme, expressing moderated responses in relation to intended behaviour towards MAR. Approximately one-quarter of respondents gave responses that indicated refusal to support the scheme.

The results also showed that there were no statistically significant differences observed based on education levels, income levels, family unit and age. In contrast, the research showed that males’ behavioural intentions toward the MAR scheme were significantly more positive than females. The resulting developed behavioural model showed that emotion and subjective norm had the strongest direct influence on intended behaviour in relation to an indirect potable MAR scheme. Fairness, trust, and perceived health and system risks also had significant influences. A notable exception was that knowledge consistently failed to contribute significantly to the prediction of intended behaviour.

Research was also undertaken into decision-making frameworks, that is, the relative relevance of a set of factors driving an individual’s ultimate decision. This research was conducted with 37 members of the Perth community and 20 technical experts. Results from this set of experiments indicated that community decision-making frameworks in relation to MAR are complex and heterogeneous, both between individuals and between different fit-for-purpose uses. The results further indicated that the perceptions of the technical experts of what factors the ‘community’ bases its decisions on were weakly correlated with the actual drivers of decision-making for most individual members of the community.

The social investigations have shown that there are a range of planning implications that are important to consider in relation to the potential introduction of MAR in urban environments such as Perth. These include dealing with the impacts of trust, risk and uncertainty; the importance of providing creditable alternatives as well as information and discussion on the complexities relating to the different water recycling options available; the need for transparent and open decision-making processes; and ensuring that communities are involved in the decision-making processes.

Health Risk Assessment

This research work package investigated the human health risks of using recycled water via MAR for irrigation purposes. It used data from the other research components as well as information from the scientific literature to determine the health risks from microbial pathogens and trace organic chemicals. An initial assessment determined that while both microbial and chemical contaminants are the main public health concerns when considering any application for the reuse of recycled water, in the case of irrigation applications using water recovered from a MAR scheme, microbial hazards are the major concern.

The microbiological risk was assessed using a Quantitative Microbial Risk Assessment (QMRA). This model used pathogen occurrence data in treated wastewater from the scientific literature, decay data from the *in situ* experiments at the infiltration gallery site, the hydrologeological assessment of residence times in the aquifer, and a number of different exposure scenarios involving irrigation to determine the risk to human health. The QMRA considered risk using three reference pathogenic microorganisms: *Cryptosporidium*, *Campylobacter* and rotavirus. Based on the acceptable risk standards in the Australian Guidelines for Water Recycling (Phase 1), the exposure risk for *Cryptosporidium* and rotavirus in the recovered recharged water was found to be marginally above the Guideline values for achieving an acceptable health risk under the experimental conditions used at the infiltration gallery site. The QMRA modelling indicated that increasing the residence time of the water in the aquifer to approximately 150 days would enable the recovered water to meet the acceptable health risk standards for class A recycled water for use in non-potable purposes.

For trace chemical contaminants, a Screening Health Risk Assessment (SHRA) methodology was developed for identifying potential health risks. In this methodology, risk quotients (RQs) were used to compare the measured chemical concentrations in the treated wastewater and the water recovered from the MAR scheme with derived health values for drinking water. Even though the intended uses for the recovered water were to be for non-potable purposes, drinking water health values had to be used as no values for non-potable water uses are currently available. Using the SHRA, chemicals that had a RQ below 1 were considered of low health significance and consequently could be ignored. Conversely, chemicals that had a RQ above 1 required additional data and a full health risk assessment.

An initial characterisation of Subiaco wastewater was conducted with respect to a range of chemicals including metals and other inorganic compounds, nutrients, natural anthropogenic organics (disinfection by-products, pesticides and endocrine disruptors), persistent organic pollutants and radio-nuclides. A total of 355 chemicals were tested for. Based on the calculated RQs, the SHRA indicated that the source water for infiltration was below health values for most of the chemicals. The exception was for N-nitrosamines and complexing agents. Five of the nine detected N-nitrosamines had RQs above 1. These chemical concentrations would be of concern if the recycled water was intended for drinking purposes; however, the overall assessment showed that they are not of health concern for recycled water used for irrigation purposes. The risk assessment for trace organics demonstrated that the detected levels of trace chemical contaminants in the Subiaco wastewater and from the Floreat Infiltration Galleries do not present a public health risk for the recovered recycled water when the water is used for non-potable purposes.

Conclusions

The research undertaken in all four components has demonstrated that MAR can be successfully used in an urban environment such as Perth. Infiltration galleries are a MAR method that can successfully combine the advantages of surface infiltration along with the benefits of being below ground, thus preventing uncontrolled access. When appropriate materials are used to construct the infiltration galleries, the research has shown that sustainable recharge using recycled water can be achieved.

Recycling water through the subsurface and through the aquifer can improve the quality of the water and achieve a recycled water that can be free of health risks to the community when used for non-potable purposes such as irrigation. Environmental risks can also be managed, however, the research demonstrated that it is very important to ensure that potential environmental hazards are assessed and MAR schemes such as infiltration galleries are designed appropriately to mitigate these hazards, achieve maximum sustainability and optimum water quality improvements.

Finally, this research project has shown that using MAR as a mechanism to assist water recycling can receive community support. This support, however, is dependent on the processes involved being seen to be transparent and open. In addition, the research has demonstrated that it is vital that the developers and operators of MAR schemes work to develop trust with the community.

1. INTRODUCTION

Managed Aquifer Recharge (MAR) involves the intentional, managed recharge of water to an aquifer. The water is then left in the aquifer for an appropriate period of time until, commonly, the water is recovered for a suitable use. MAR can be used as a cheap, safe storage medium and has been recognised to have benefits of being able to improve the quality of the recharged water (Dillon et al., 2008). This can make MAR a potentially efficient tool to assist in the recycling of water.

Western Australia possesses a number of aquifers that have the potential to be used for MAR (Martin et al., 2004). The type of MAR and the water source used for these aquifers will depend on the depth and degree of confinement of the aquifer and the existing uses for the aquifer. For example, on the Swan Coastal Plain in the south-western region, it would be considered most appropriate to use well injection for the deeper confined Leederville or Yaragadee aquifers whereas a surface infiltration method may be easier and more preferable for the unconfined superficial aquifer. Also, only high quality water should be recharged to an aquifer that is used for potable purposes or in the vicinity of drinking water wells. In comparison, in other regions, water of a lower quality may be able to be recharged for later recovery for non-potable uses.

In Western Australia, much of the interest in MAR has focused on the Swan Coastal Plain as this is the location of the capital city, Perth, which has the majority of the state's population. As a large area of the Swan Coastal Plain is urbanised, any MAR scheme would therefore need to meet a range of social, environmental and health requirements. In addition, while urban areas are ideal for potentially reusing large volumes of water, and MAR can be an efficient mechanism to achieve this, there can be challenges to achieve these goals. Some of these challenges involve minimising uncontrolled community exposure to the recycled water; the cost of land required for running an MAR scheme; and the management and operation of MAR schemes. Before MAR can be considered as a viable means to recycle water a series of questions need to be addressed relating to the sustainability of recharge. These include water quality issues; health impacts of pathogens and organic chemicals; and the social acceptability of MAR.

To answer these questions a three-year multidisciplinary research project was established. The aim of the project was to test an efficient MAR method for its suitability in urban environments and to investigate the management requirements, water quality issues, potential health impacts, and social acceptance of MAR. The research was divided into four interlinked work packages to cover the wide range of topics that needed to be covered and to investigate the different aspects of an MAR scheme operating in an urban setting.

The first work package focused on field studies testing the suitability of infiltration galleries for urban MAR schemes. This included research on the sustainability of the infiltration gallery design, water quality changes that occurred during recharge and the residence time in the aquifer, issues relating to recharge and passage of recycled water through the aquifer, as well as operational and management requirements for operating such schemes.

The second work package undertook specific research on selected trace organic chemicals in urban aquifers during MAR. Trace organics have become of concern to regulators and the general public alike, and the aim of this work package was to determine the fate and behaviour of trace organics during recharge and residence through the aquifer. The investigations for this work package were done using laboratory column experiments.

The third work package focused on the social acceptability of MAR. While the science of recycling water via MAR has achieved major advancements in the last decade, the attitude of the public has yet to be tested. There are numerous examples of water recycling schemes that had failed due to public resistance and it was therefore considered important to obtain a better understanding of the processes involved in forming community attitudes, both positive and negative, to water recycling and MAR. For MAR, there were some indications that the public were more in favour of recycling water through the use of aquifers than by other means (Po et al., 2005). It was felt, however, that a more intensive study was needed to determine the actual factors driving the attitudes and decisions the community made about the role of MAR in water recycling.

The fourth work package undertook an assessment of the potential health risks from microbial pathogens and trace organic chemicals in the water recovered from MAR schemes. This work package used research results from the other work packages (specifically Work Packages 1 and 2) and information from the Australian Guidelines for Water Recycling and the scientific literature to determine the health risk to the general community from pathogens and trace chemicals through exposure to the recovered water when used for non-potable purposes.

This report provides the final findings from the three years of research undertaken by this project.

2. DESIGN AND OPERATION OF INFILTRATION GALLERIES AND WATER QUALITY CHANGES

2.1. Aims and Objectives of Work Package

A major research aim for the Managed Aquifer Recharge (MAR) project was to determine the applicability of MAR in urban areas of the Swan Coastal Plain. There are a range of MAR methods (e.g. well injection, pond infiltration, soil aquifer treatment) and recharge water sources (e.g. drinking water, urban stormwater, treated wastewater). For this project, infiltration galleries using secondary treated wastewater were tested. Infiltration galleries have a number of advantages: they are cheaper and less sophisticated to operate than well injection systems; they are potentially less prone to clogging than injection wells; they are subsurface and thus take up no valuable ground area (as compared to pond-based systems) and prevent unsupervised access to the recharging water by the community, domestic animals or wildlife; and their lack of exposed water means that there is no chance for mosquito breeding in the water prior to recharge.

Infiltration galleries have been used in other regions of the world but primarily to recharge potable quality water or tertiary treated wastewater to aquifers; however, there has been little testing of infiltration galleries to recharge secondary treated effluent to an unconfined aquifer (Peter Dillon, CSIRO, personal communication, 2005). The Swan Coastal Plain is potentially ideal for using infiltration galleries as it consists, particularly in the coastal areas, of coarse sand overlying limestone in which lies a shallow unconfined aquifer.

Two sites were used to address a number of objectives, both research and technical:

- to monitor recharge of water and determine clogging rates during aquifer recharge at the field sites
- to determine microbiological die-off during infiltration to, and residence time in the superficial aquifer
- to identify water quality improvements that occur during the recharge of recycled water to groundwater
- to test existing and novel treatment technologies to establish suitability of the proposed applications for use with different MAR technologies to produce appropriate fit-for-purpose water
- to characterise aquifers identified as potential MAR sites to determine factors influencing recharge and recovery efficiencies
- to identify management and operational requirements that are needed to ensure that future MAR schemes are operated in a manner that optimises the economic and environmentally suitable use of reclaimed waters, while managing apparent and inherent operational, health and environmental risks.

The main results from this component of the project are summarised below. Details of the methodology and more results concerning the design and operation of infiltration galleries and the accompanying water quality changes are presented in the complete final report of this project.

2.2. MAR Infrastructure and Monitoring Equipment

MAR trial sites

To test the applicability of infiltration galleries, two experimental field sites for MAR were established. One was located at the Halls Head Wastewater Treatment Plant in Mandurah, and the second installed at the CSIRO Centre for Environment and Life Sciences in Floreat, Perth (Figure 1). The MAR trials were installed in different geological settings and under different hydrogeological conditions to compare gallery performance and to investigate the relevance for water quality changes. Both sites have minimal topographic variation but, unlike the grassy sheep paddock at the Floreat site, the Halls Head site had drier, weedy surface vegetation that was periodically removed.

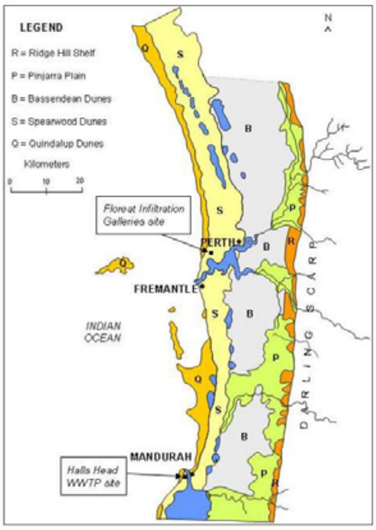

Figure 1. Location map showing the geomorphology and soils on the Swan Coastal Plain (after McArthur and Bettenay, 1974) and the MAR research sites

Design and construction of infiltration galleries

The original set of infiltration galleries at both sites consisted of one gravel-filled gallery and one Atlantis Leach System® gallery (Figure 2). The latter is a series of modular, lightweight, polypropylene crates. The only visible sign of the MAR operation underground was the inspection lid (Figure 3). The source of the secondary treated wastewater at Floreat was the Subiaco Wastewater Treatment Plant and at Halls Head it was the Halls Head Wastewater Treatment plant.

Groundwater monitoring bores

To compare water quality changes at the Floreat Infiltration Galleries MAR site with the surrounding aquifer, a number of groundwater bores were installed. Three 'background' bores were located hydraulically up-gradient. A series of 'monitoring' bores were installed in close proximity with slotted intervals positioned to intercept the recharge plume at different depths (Figure 4). An extraction (recovery) bore was installed at a distance of 50 m down-gradient from the infiltration galleries with a daily flow of 250 kilolitres per day. At the site of the Halls Head MAR trial, where a previous study had been conducted involving managed aquifer recharge via pond infiltration, there were a number of pre-existing monitoring bores to sample and data to use for interpreting changes in water chemistry.

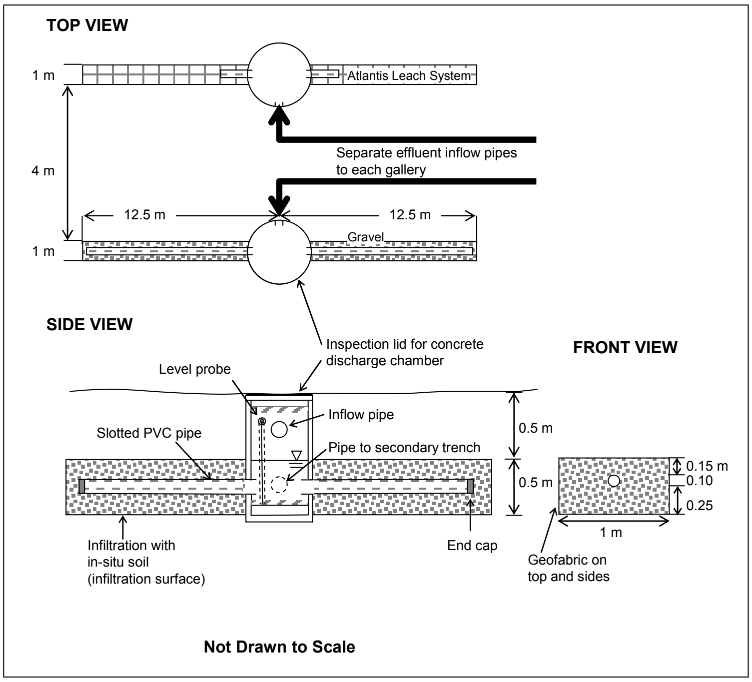

Figure 2. Schematic of the covered infiltration galleries as originally installed at the Floreat site

Figure 3. Installation of the two infiltration galleries in Floreat. The top left photo shows the Atlantis Leach System®; the bottom photo shows the gravel-filled gallery and the scored PVC pipe that distributed treated effluent to the ends of the gallery. The inspection points for viewing effluent inflow to each gallery are highlighted in the top right photo.

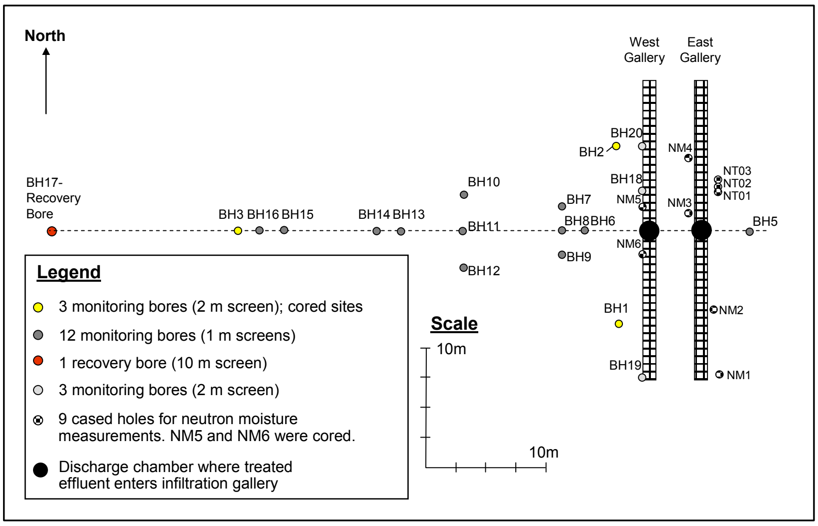

Figure 4. Map view of the Floreat site showing the positions of the monitoring bores, the recovery bore, the neutron moisture meter access tubes and the two infiltration galleries

Table 1. Submersible probes

Probe designation	Water parameters* recorded	Locations used
Troll® 9000; Troll® 9500 from In-Situ Inc.	pressure, temp, turb, ORP, pH, DO, EC	Floreat: BH8, BH10, BH16, BH17 Halls Head: HH_E1
Odyssey capacitance water level probe from DataFlow Systems Pty Ltd	water level	Floreat: both galleries, BGRND01, BH6, BH7, BH15 Halls Head: both galleries, 2/84, HH_E2,
Odyssey conductivity and temperature probe from DataFlow Systems Pty Ltd	EC and temp	Floreat: BH1, BH2, BH6, BH7, BH8, BH9, BH13, BH18, BH19, BH20, west gallery
Levelogger from Solinst Ltd	water level, temp, EC	Floreat: BH1, BH16 Halls Head: HH_W2
Yeo-Kal Pty Ltd	temp, EC, SAL, DO, pH, ORP, turbidity	Floreat: west gallery

* DO (dissolved oxygen), EC (electrical conductivity), ORP (oxidation-reduction potential), temp (temperature), turb (turbidity), SAL (salinity).

Table 2. Microbial pathogens and indicators used in pathogen decay experiment

Microorganism	Source
E. coli	laboratory strain ACM[1] 1803
Enterococcus faecalis	laboratory strain ACM 2517
Campylobacter jejuni	laboratory strain ACM 3393
Salmonella typhimurium	laboratory strain ACM 13311
Coxsackievirus	laboratory strain Type B1
Adenovirus	laboratory strain Type 3
Rotavirus	faecal isolate
Cryptosporidium oocysts	faecal isolate

[1] ACM = Australian Collection of Microorganisms.

Water quality monitoring

To monitor changes in water quality and water level within the aquifer and within the infiltration galleries, several different types of data recording probes were used at the two MAR sites (Table 1).

In addition to physical measurements, water samples were analysed for inorganic and organic chemicals and microbes. A pathogen decay study was undertaken for a number of microbial pathogens (Table 2) using a series of diffusion chambers (Figure 5) suspended down one of the monitoring bores at the Floreat site. The determination of a rate of decay for specific microbial pathogens allows a risk assessment to be done that establishes exposure risk for that pathogen in the recovered water.

Figure 5. Diffusion chambers in field prior to lowering into groundwater for survival experiment

2.3. Results[1]

2.3.1. Recharge Rates and Operation of the Infiltration Galleries

A preliminary investigation of the infiltration capacity of the Spearwood sands at the Floreat site revealed that the characteristics of the sand were quite favourable for infiltrating large volumes. Infiltrometer results suggested that each gallery could infiltrate approximately 955 litres per minute based on a hydraulic loading rate of 55 m/day and an infiltration area for each gallery of 25 m^2. The galleries were thus designed to infiltrate only 17.5 litres per minute (1 m/day) to prevent any potential clogging of the infiltration galleries in the early stages of operation. With the galleries receiving a continuous combined volume of 50 kilolitres per day for most of the project's duration, approximately 36.7 megalitres of treated effluent were infiltrated via the two infiltration galleries over a 39-month period (Figure 6).

[1] The majority of this section refers to the Floreat site. Results from the Halls Head site are not included as the results obtained were intermittent due to maintenance problems at this remotely operated and monitored wastewater treatment plant and the fact that this site was decommissioned earlier than anticipated. Details on the interpretation of water quality and water level changes observed at Halls Head are provided in the complete final report.

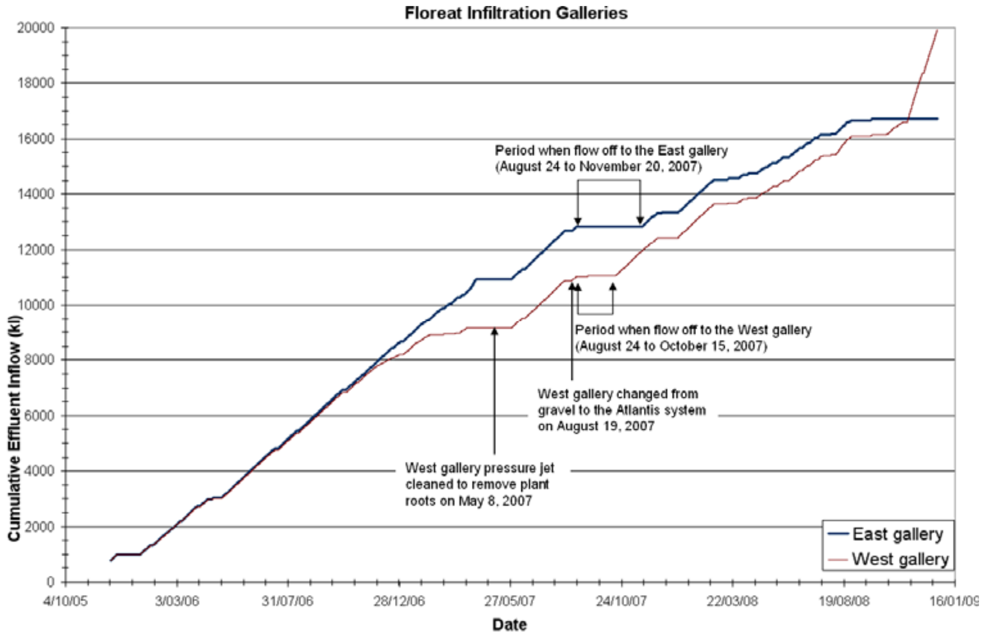

Figure 6. The history of cumulative effluent inflow to the infiltration galleries. The west gallery was originally gravel-filled. It was replaced with an Atlantis Leach System®, similar to the east gallery, on August 19, 2007.

During the first 13 months of operation at Floreat, both galleries recharged the same volume of wastewater. The earliest signs of clogging occurred in the gravel-filled gallery in July 2006. Subsequently over the next three months, the water level increased in the gravel gallery at a rate of approximately 0.6 mm/day, whereas the water level in the Atlantis Leach System® gallery remained relatively constant (Figure 7). While it was never absolutely clear what actually was causing the clogging in the gravel-filled gallery, the presence of plant roots would have, at least, caused some of the problem. No plant roots were observed in the central discharge chamber of the gallery constructed using the Atlantis Leach System®, although they potentially were growing in the voids of the crates. Even if this occurred, it did not have any noticeable effect on infiltration from the east gallery. In August 2007, the gravel gallery was replaced with Atlantis Leach System® crates similar to the east gallery.

During the final two months of operation, the east Atlantis Leach System® gallery was shut-off and the inflow rate to the west gallery was increased from 17.5 L/min to between 50 and 67 L/min to test the feasibility of increasing infiltration rates (Figure 6). There was no evidence of clogging in the Atlantis Leach System® gallery during this two month period of observation.

The unsaturated zone beneath the Floreat infiltration galleries has been fairly well characterised from coring and analysis of the sediments. There is roughly 7 m of Spearwood sand overlying Tamala Limestone, depending on the cored location. The water table is generally below a depth of 10 m below ground surface, but seasonal variations are on the order of ± 1 m and there is no evidence to suggest that a substantial increase in the water table occurred beneath the galleries due to recharge.

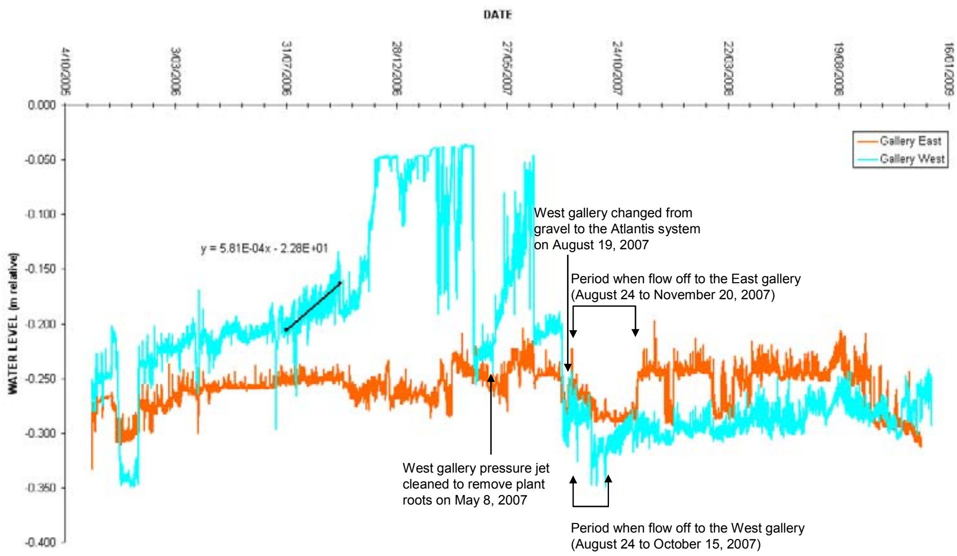

Figure 7. Comparison of water levels in the east and west galleries. The periods when inflow of wastewater to the galleries was deliberately off due to the tracer tests in August–October 2007 are labelled on the plot.

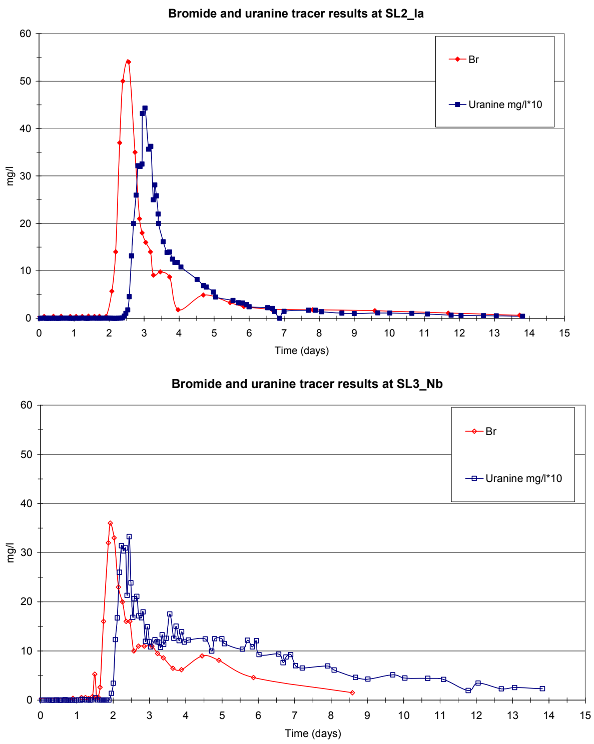

Figure 8. Bromide versus uranine breakthrough curves for lysimeters SL2_Ia (6.81 m below the west gallery) and SL3_Nb (6.62 m below the west gallery)

Tracer tests using bromide and the fluorescent compound uranine were undertaken to further characterise the unsaturated zone. The analysis of breakthrough curves from the main tracer experiment, which involved infiltrating bromide and uranine concurrently, revealed a considerable amount of information about variability in flow velocities within the unsaturated zone as well as differences in the results using uranine versus bromide. The average t_{mean} for the three deepest (8.80–9.15 m) sampling points based on the uranine results is 5.7 days ± 1.5 days. This is a possible minimum estimate of the mean effective flow time from the base of the gallery to the water table. If there is sorption of uranine, then a conservative tracer such as bromide will yield a lower estimate for the travel time, as was found at depths between 6.6 m and 6.8 m below the west gallery (Figure 8 and Table 3).

Table 3. Mean effective flow times (t_{mean}) interpreted based on the breakthrough curves for the uranine and bromide tracers

Depth below west gallery (m)	Uranine tracer t_{mean} (days)	Bromide tracer t_{mean} (days)
0.50	0.82	--
0.50	1.05	--
0.50	0.68	--
0.50	0.68	--
2.51	1.46	--
2.63	1.65	--
2.71	1.36	--
4.44	2.80	--
4.67	3.21	--
4.84	2.67	--
4.94	3.99	--
6.42	2.28	--
6.62	5.16	3.28
6.81	3.52	2.97
8.80	5.05	--
8.89	4.57	--
9.15	7.42	--

(--) Indicates not measured.

2.3.2. Recharge Water Residence Time in the Aquifer and Dilution with Background Groundwater

A contrast in salinity and major ion composition existed between the initial groundwater chemistry at the Floreat site and the treated effluent infiltrated to the Tamala aquifer. The salinity of the treated effluent was marginally higher than the ambient groundwater (total dissolved solids of 750 and 640 mg/L, respectively) and comprised predominantly of sodium chloride. The average concentrations of calcium (Ca), chloride (Cl), sodium (Na) and potassium (K) in the recharge water and background groundwater (before the MAR trial) are distinctly different (Table 4).

This difference in water quality provided a means of estimating the breakthrough time of recharge water at locations down-gradient of the galleries by monitoring when the groundwater chemistry sampled from the monitoring bores resembled that of the recharge water. Some bores did not show a transition in groundwater chemistry due to either being slotted below the recharge plume or because they contained a large proportion of background groundwater due to proximity to the extraction bore and its high pumping rate. However, although the groundwater major ion chemistry data provided qualitative evidence of down-gradient breakthrough of the recharge plume, there were not enough data to accurately determine breakthrough times at intermediate bores between the galleries and the extraction bore. Ideally, one would acquire the breakthrough time at the extraction bore, but the large pumping rate created considerable dilution which made it difficult to distinguish the chemical signature of the recharge water from that of the background groundwater.

A quantitative modelling approach (using a three-dimensional MODFLOW-MODPATH simulation) was used to predict breakthrough times for chloride and the mixing fraction of recharge water present in groundwater sampled from bores down-gradient from the galleries. A range of minimum travel times between 43 and 107 days (depending on the transport parameters used in the model) was obtained for water that was recharged to the aquifer and recovered 50 m down-gradient (Table 5).

Table 4. Comparison of average [and standard deviations] of calcium, chloride, sodium and potassium concentrations in the recharge water sampled from the infiltration galleries and the background groundwater sampled from bores BGRND01, BGRND02 and BGRND03

Water sources	Calcium (mg/L)	Chloride (mg/L)	Sodium (mg/L)	Potassium (mg/L)
Recharge water in the infiltration galleries	28.6 [±9.5]	245.29 [±62]	194.00 [±44]	22.9 [±3.5]
Background groundwater from BGRND01, BGRND02 and BGRND03	98.8 [±23.5]	162 [±27]	92.6 [±14.5]	4.96 [±0.83]
Ratio of average concentration in recharge water to background groundwater	0.29	1.51	2.10	4.62

Table 5. Minimum travel times within the aquifer predicted by MODPATH

Model	Permeability (m/day)	Porosity (%)	Minimum travel time (days)
1	30	20	72
2	75	20	50
3	100	20	43
4	30	30	107
5	75	30	75
6	100	30	65

These results were based on models that apply the transport parameters uniformly to the aquifer, but heterogeneity and lateral variation in aquifer properties within the sandy limestone was revealed by the model calibration results. Although these spatial variations could not be resolved by modelling with the available calibration data, an estimation of the minimum residence time in the saturated zone at the Floreat Infiltration Galleries site was determined to be approximately 70 days between the galleries and the extraction bore

Based on a transport model calibrated with chloride data, the estimated maximum dilution with background groundwater was 80% at the extraction bore (BH17), with a pumping rate of 250 KL/day (i.e. the recovered water consisted of 20% recharged water/80% groundwater) (Table 6). The uniform permeability models with 30 m/day and 100 m/day for the Tamala Limestone are shown as they appear to fit the chloride data better at the east and west ends of the field site, respectively. A higher permeability field produces shorter travel times and thus a worst-case scenario for breakthrough of contaminants.

Table 6. Estimated proportion of recharge water in groundwater

Bore	Estimated fraction of recharge water in groundwater based on model with permeability of 100 m/day	Estimated fraction of recharge water in groundwater based on model with permeability of 30 m/day	Average fraction of recharge water in groundwater [Standard Deviation]
BH1	1.00	1.00	1.00 [±0.00]
BH6	0.94	0.95	0.95 [±0.00]
BH7	0.76	0.79	0.77 [±0.02]
BH8	0.69	0.74	0.72 [±0.04]
BH10	0.67	0.69	0.68 [±0.01]
BH11	0.16	0.52	0.34 [±0.25]
BH13	0.57	0.66	0.62 [±0.06]
BH15	0.55	0.65	0.60 [±0.07]
BH16	0.44	0.63	0.54 [±0.13]
BH17	0.19	0.24	0.21 [±0.04]

2.3.3. Water Quality Changes

Inorganic chemicals and basic water quality parameters

This section provides results on inorganic chemistry sampling and field measurements that are relevant to evaluating the suitability for irrigation water quality.

Physical and chemical characteristics of water sampled or measured from selected bores at the Floreat Infiltration Galleries site are summarised in Table 7. The slotted intervals in the monitoring bores (BH1, BH8, BH12, BH16 and BH17) shown in Table 7 intersect the flow-path of the recharge plume, whereas the three background bores are up-gradient.

Concentrations of twenty analytes in the water samples were compared to trigger values according to ANZECC & ARMCANZ (2000). Trigger values are defined as long term (the maximum concentration in the irrigation water which can be tolerated assuming 100 years of irrigation) or short term (the maximum concentration in the irrigation water which can be tolerated for a shorter period, i.e. 20 years).

None of the water samples from the galleries or bores exceeded the short-term trigger values for any of the analytes apart from phosphate; phosphate only exceeded the trigger value in the wastewater entering the galleries and in the bore closest to the galleries (BH01). Long-term trigger values were exceeded for some of the other analytes at some of the monitoring points. Apart from iron, however, all of the values higher than the long-term trigger values occurred in the monitoring bores closest to the infiltration galleries. From bore BH11 (i.e. from midway through the monitoring field) to the recovery bore, iron and total nitrogen were the only analytes that had values exceeding the trigger values and total nitrogen was only high in one bore (BH14). Iron is known to be a problem in many bores on the Swan Coastal Plain and the high values obtained are a reflection of management issues for any pumping bore on the Swan Coastal Plain, not just for MAR schemes.

Organic chemicals

Water samples from selected bores at the Floreat Infiltration Galleries site were tested for five pharmaceuticals (Table 8). Diazepam and phenytoin were not detected in any of the 152 measurements analysed for each chemical. The percent of samples (excluding blanks) that had concentrations greater than detection limits for the other three pharmaceuticals were temazepam (59%), oxazepam (59%) and carbamazepine (40%).

Samples collected from bores containing mainly ambient or native groundwater (such as the background bores, BH11 and BH17) had concentrations that were predominantly below detection limits. The concentrations of carbamazepine and oxazepam, and to a lesser extent temazepam, were observed to reduce in monitoring bores down-gradient from the recharge source (Figure 9). Based on mass recovery rates, a field assessment of carbamazepine revealed no degradation of this compound would occur during the estimated travel time of 70 days through the aquifer. Using the ratio of oxazepam to the conservative carbamazepine, it was determined that there was no evidence to suggest that biodegradation of oxazepam was occuring, although due to dilution, the measured oxazepam concentrations were below detection levels in the recovered water. Column experiments supported this finding.

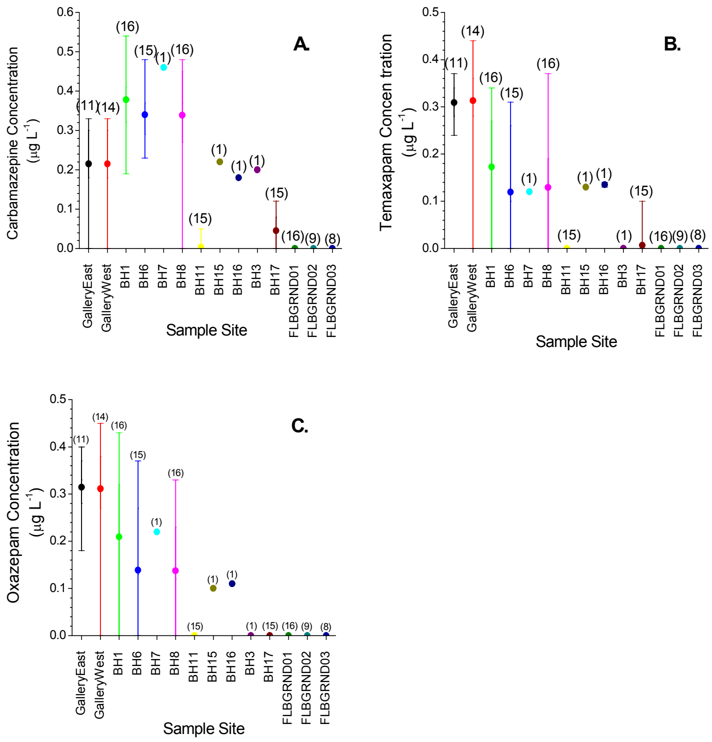

Figure 9. Detection of (A) carbamazepine; (B) temazepam; and (C) oxazepam in the groundwater in monitoring bores along the Floreat Infiltration Gallery site

Table 7. Water characteristics sampled from the Floreat Infiltration Galleries site. The mean and (±SD) values are indicated for each of the parameters*.

Parameter (Unit of Measure)	**East and West galleries**	**BH1**	**BH8**	**BH12**	**BH16**	**BH17**	**Background bores**
Water temperature (^oC)	24 (±4)	24 (±4)	23 (±3)	23. (±2)	22 (±1)	22 (±2)	22 (±1)
pH	7.33 (±1.11)	7.58 (±0.78)	7.42 (±0.69)	7.45 (±1.43)	7.32 (±1.08)	7.41 (±1.07)	7.04 (±0.88)
Suspended Solids (mg L^{-1})	7.5 (±7.05)	56.4 (±45.38)	8.6 (±4.98)	8 (±2.83)	12 (±4.24)	7.25 (±3.59)	2 (±3.46)
Total Dissolved Solids (mg L^{-1})	755 (±179)	831 (±140)	784 (±116)	773 (±85)	763 (±29)	681 (±17)	644 (±25)
Electrical Conductivity (mS m^{-1})	147 (±57)	154 (±54)	148 (±58)	155 (±69)	140 (±54)	131 (±48)	129.09 (±65.69)
Eh (mV-SHE)	385 (±184)	393 (±160)	354 (±175)	285 (±161)	275 (±161)	169 (±121)	321 (±189)
Dissolved Oxygen (mg L^{-1})	2.15 (±1.82)	6.6 (±2.53)	5.87 (±3.28)	3.28 (±2.27)	4.61 (±2.73)	2.8 (±1.69)	4.02 (±2.56)
Cl (mg L^{-1})	245 (±62)	247 (±51)	232 (±41)	223 (±24)	184 (±24)	186 (±8)	162 (±27)
HCO_3 (mg L^{-1})	174 (±24)	273 (±23)	278 (±8)	292 (±30)	282 (±39)	291 (±8)	276 (±59)
SO_4 as S (mg L^{-1})	64.1 (±8)	63.0 (±7)	66.1 (±8)	81.2 (±10)	75 (±11)	59 (±6)	64.5 (±18)
Na (mg L^{-1})	194 (±44)	183 (±51)	184 (±44)	156 (+42)	135 (±34)	117 (±10)	92.6 (±15)
Ca (mg L^{-1})	28.6 (±9.5)	63.7 (±12.6)	68.8 (±14.1)	94.7 (±13.2)	87.5 (+18.7)	96.6 (±5.3)	98.8 (±23.5)
Mg (mg L^{-1})	11.6 (±4.5)	12.2 (±4.3)	11.5 (±2.6)	13.0 (±1.3)	13.5 (±2.2)	15.0 (±0.7)	13.2 (±3.2)
K (mg L^{-1})	22.9 (±3.5)	20.6 (±5.4)	19.8 (±5.4)	18.5 (+5.4)	11.9 (±3.5)	9.3 (±1.8)	4.96 (±0.83)
Fe (mg L^{-1})	0.14 (±0.20)	0.049 (±0.052)	0.18 (±0.49)	2.2 (±1.7)	1.1 (±1.0)	2.6 (±1.4)	0.44 (±0.72)
Mn (mg L^{-1})	0.036 (±0.016)	0.0043 (±0.005)	0.035 (±0.056)	0.043 (±0.021)	0.045 (±0.019)	0.021 (±0.002)	0.013 (±0.009)
B (mg L^{-1})	0.21 (±0.08)	0.21 (±0.09)	0.18 (±0.06)	0.12 (±0.06)	0.069 (±0.036)	0.052 (±0.024)	0.085 (±0.090)
TOC (mg L^{-1})	9.98 (±3.8)	6.32 (±3.53)	5.67 (±3.02)	3.57 (±1.51)	3.14 (±3.53)	4.88 (±3.79)	2.51 (±2.72)
DOC (mg L^{-1})	10.86 (±2.35)	6.27 (±3.04)	5.11 (±3.02)	4 (±1)	5 (±2.83)	5.09 (±2.91)	2.73 (±2.15)
N_Total (mg L^{-1})	4.27 (±1.9)	4.78 (±2.02)	3.96 (±2.13)	0.44 (±0.44)	0.16 (±0.12)	1.58 (±0.49)	0.29 (±0.36)
NO_3_N (mg L^{-1})	2.16 (±1.41)	3.72 (±1.68)	3.28 (±2.13)	0.25 (±0.41)	0.02 (±0.02)	0.99 (±0.43)	0.15 (±0.25)
Soluble reactive phosphorus as P (mg L^{-1})	6.31 (±3.32)	1.96 (±1.6)	0.01 (±0.01)	<0.005#	<0.005#	0.01 (±0.01)	0.01 (±0.01)

* For the number of samples used to determine mean and standard deviation for each analyte at each monitoring bore see Table 1D-2 in Appendix 1D; # Below detection limit.

Table 8. Detection of pharmaceuticals in the galleries and groundwater at the Floreat Infiltration Gallery site

	Mean Pharmaceutical Concentration ($\mu g\ L^{-1}$)				
Bore	**Carbamazepine**	**Diazepam**	**Oxazepam**	**Phenytoin**	**Temazepam**
Gallery East	0.202 (±0.038)	0	0.315 (±0.067)	0	0.309 (±0.042)
Gallery West	0.215 (±0.084)	0	0.311 (±0.108)	0	0.313 (±0.108)
BGRND01	0	0	0	0	0
BGRND02	0	0	0	0	0
BGRND03	0	0	0	0	0
BH01	0.378 (±0.089)	0	0.209 (±0.143)	0.006 (±0.025)	0.172 (±0.119)
BH03	0.2 (±0)[1]	0	0	0	0
BH06	0.34 (±0.068)	0	0.139 (±0.137)	0	0.119 (±0.129)
BH07	0.46 (±0)[1]	0	0.22 (±0)[1]	0	0.12 (±0)[1]
BH08	0.339 (±0.145)	0	0.137 (±0.123)	0.006 (±0.025)	0.129 (±0.123)
BH11	0.003 (±0.013)	0	0	0	0
BH15	0.22 (±0)[1]	0	0.15 (±0)[1]	0	0.13 (±0)[1]
BH16	0.18 (±0)[1]	0	0.11 (±0)[1]	0	0.135 (±0.007)[1]
BH17	0.045 (±0.042)	0	0	0	0.007 (±0.026)
Guideline value[2]	100 $\mu g\ L^{-1}$	2.5 $\mu g\ L^{-1}$	NA[3]	NA[3]	5 $\mu g\ L^{-1}$

[1] Value from one sample only.
[2] NRMMC-EPHC-NHMRC (2008).
[3] NA = Not available.

Microorganisms

The results for the average, maximum and minimum detection of faecal coliforms and enterococci at the Floreat Infiltration Gallery site can be seen in Figures 10 and 11. The results show that high numbers of faecal coliforms and enterococci were routinely detected in the treated wastewater entering the infiltration galleries with average faecal coliform numbers of around 8000 colony forming units (cfu) 100 mL-1 and average enterococci numbers of 10000–12000 cfu 100 mL-1. These numbers should be considered normal for treated wastewater. Once the treated wastewater recharged through approximately 10 m of unsaturated zone, the average number of faecal coliforms dropped to approximately 50 cfu 100 mL-1 or less in the monitoring bore closest to the infiltration galleries (BH01).

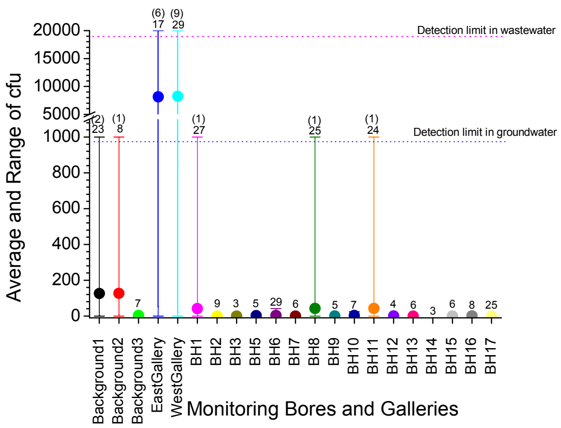

Figure 10. Average, maximum and minimum numbers of faecal coliforms (per 100 mL) detected at all monitoring sites at the Floreat infiltration galleries over the time of the pilot project. (Numbers on top of each site value are the total number of samples used in this analysis. Numbers in parenthesis are the number of times counts above the maximum detection limit were obtained).

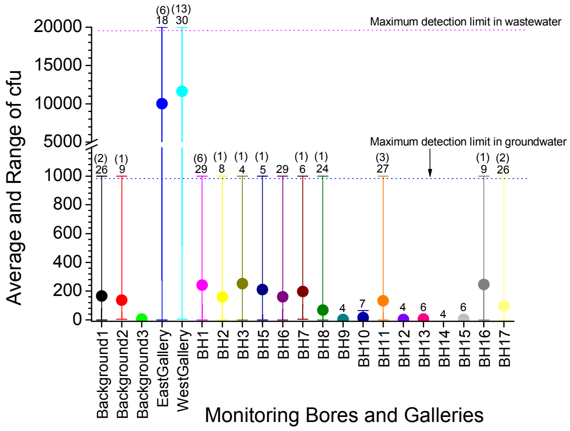

Figure 11. Average, maximum and minimum numbers of enterococci (per 100 mL) detected at all monitoring sites at the Floreat infiltration galleries over the time of the pilot project. (Numbers on top of each site value are the total number of samples used in this analysis. Numbers in parenthesis are the number of times counts above the maximum detection limit were obtained).

It is worth noting here that both faecal coliforms and enterococci were detected in the background groundwater up gradient of the infiltration galleries indicating that the local groundwater is subject to contamination from sources other than the recharged treatment wastewater. The fact that sheep use the experimental paddocks on and around the site of the infiltration galleries is a strong suggested link to these microbes. Despite the best efforts of the field sampling team the use of sampling pumps connected to long hose lines means that occasionally, inadvertently pump-lines come into contact with the ground. If there were fresh sheep droppings in the vicinity this could cause contamination of the pump lines which then could cause brief contamination of the water within the monitoring bores. If it is assumed that sheep faecal material is the source of these microorganisms in the aquifer, this indicates that potential surface contamination remains an issue that will need consideration for any infiltration galleries or similar MAR scheme that is planned for the superficial aquifer in the Perth region and an intensive assessment of potential contamination sources will be needed.

The results from the monitoring for F^+ specific bacteriophage and enteric viruses are given in Table 9. As could be expected, the treated wastewater in the infiltration galleries was positive for phage in more than 90% of the samples tested and a similar result was obtained for the PCR detection of adenovirus. In general, the detection of bacteriophage, adenovirus and enterovirus declines with increasing distance from the infiltration galleries.

The overall results of the microbiological monitoring show that the microbiological quality of the recharged water/groundwater is much better than the treated wastewater entering the infiltration galleries with a minimum 3 log removal of microorganisms from the recharged recycled water between the infiltration galleries and the recovery well (BH017). This indicates that the galleries are acting as an active treatment barrier for pathogen removal and producing a water quality that should be suitable for irrigation of green open spaces, at least where the potential for exposure is controlled.

Table 9. The detection of F^+ specific bacteriophage, adenovirus and enterovirus in samples collected from the infiltration galleries and monitoring bores

Monitoring site	F^+ specific phage (per 50 mL or 500 mL)[a]		Adenovirus (per 1 L or 5 L)[b]		Enterovirus (per 1 L or 5 L)[b]	
	+ve	-ve	+ve	-ve	+ve	-ve
BGRND01	**2**	17	0	3	0	3
BGRND02	0	8	-	-	-	-
BGRND03	0	6	-	-	-	-
BH05	0	3	0	4	0	3
Gallery East	**13**	1	**1**	2	-	-
Gallery West	**25**	1	**12**	4	**1**	5
BH01	**1**	24	0	18	**1**	4
BH02	0	8	0	2	0	1
BH03	0	1	-	-	-	-
BH06	0	25	0	10	0	3
BH07	0	4	-	-	-	-
BH08	0	23	**1**	6	0	2
BH09	0	2	-	-	-	-
BH010	0	3	-	-	-	-
BH011	**1**	22	0	9	0	3
BH012	0	1	-	-	-	-
BH013	0	4	-	-	-	-
BH014	-	-	-	-	-	-
BH015	0	1	0	1	-	-
BH016	0	3	0	1	-	-
BH017	0	18	0	6	-	-

[a] 50 mL of treated wastewater or 500 mL of groundwater.
[b] 1 Litre of treated wastewater or 5 Litres of groundwater.
- = No testing was undertaken.

Microbial pathogen decay rates

It is recommended by the Australian Water Recycling Guidelines, in the Managed Aquifer Recharge section, that if the aquifer is to be relied upon for the removal of microbial pathogens that a pathogen decay study be undertaken at the site (NHMRC-EPHC-NRMMC, 2009). The outcomes of the decay study conducted as part of this project are presented as a decay rate (λ) and the corresponding T90 value (time for a 90% reduction) for each of the pathogens tested (Table 10). As has been previously observed (Toze and Hanna, 2002; Toze et al., 2004; Yates et al., 1990), the results demonstrate that the aquifer has an active treatment capacity to remove pathogens during passage of recharged water, particularly given the estimated travel time of 70 days through the aquifer.

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Table 10. Decay rates (λ) and 90% removal times (T90) of microbial pathogens in groundwater at the Floreat Infiltration Gallery site through the use of *in situ* pathogen decay chambers in monitoring bore BH06

Enteric microbe tested	λ (day^{-1})	T90 (days)
Cryptosporidium	-0.0269 (±0.0018)	37
Adenovirus	-0.0178 (±0.0116)	56
Rotavirus	-0.0291 (±0.0067)	34
Coxsackievirus	-0.0539 (±0.0012)	18.5
MS2	-0.1277 (±0.0008)	8
E. coli	-0.6547 (±0.1328)	1.5
S. typhimurium	-0.8428 (±0.0454)	1
E. faecalis	-0.8942 (±0.0004)	1

2.4. Lessons Learnt: Management and Operational Requirements for MAR Systems in Western Australia

During the establishment and operation of the infiltration galleries and the associated research within this project, a number of previously unforseen practical issues were encountered and dealt with. Also, since the commencement of the project, the New Australian Water Recycling Guidelines have become available (NRMMC-EPHC, 2006) which include a dedicated section on Managed Aquifer Recharge (NHMRC-EPHC-NRMMC, 2009). Many of the issues relating to setting up an MAR scheme that needed to be investigated and established during the commencement of the infiltration galleries are now covered in these new guidelines. There were, however, a number of lessons learnt during this project that are either specific to the Swan Coastal Plain or are not specifically mentioned in the Australian Guidelines. The authors consider that these issues are worth listing for consideration and it is hoped that this information will assist in the design and operation of new MAR schemes. A more complete explanation of these issues is found in the complete project report.

Infiltration System Design

It was demonstrated that the use of appropriate materials for the design and establishment of MAR schemes needs to be carefully considered. It is strongly recommended that the materials used to construct any proposed MAR scheme be considered based on a range of criteria that includes, but is not dominated by initial construction costs. For example, the results of the research did in fact show that, while the Atlantis Leach System® was more expensive than gravel for constructing the infiltration galleries, its long-term superior performance meant that the greater initial outlay was far outweighed by the reduced maintenance costs.

Reliability of Water Supply

An understanding of the security and reliability of supply of the recharge water and designing the system to cope with supply issues will be an important issue in managing and operating any new MAR scheme. For example, in the current scheme both sets of infiltration galleries (Floreat and Halls Head) were designed to be continually supplied with secondary treated wastewater from the respective wastewater treatment plants, not taking into account the impact of low flow events associated with the diurnal cycle of wastewater.

Iron Precipitation and Fouling of Pumps

Pumps are an integral part of any MAR scheme, used in the delivery of the recharge water from the source to the scheme, sometimes to assist with the recharge, and then for recovery of the recharged water from the aquifer. The importance of the condition of the pump and fouling around the pump and MAR wells is well documented (e.g. Dillon and Toze 2005). The recovery pump (in BH17) suffered from iron fouling which highlighted the need for periodic maintenance. The problem of clogging was found to be easily remedied by regular visual inspections of the pump screen, monitoring of the flow rate of the treated wastewater entering the infiltration galleries, and the establishment of a regular cleaning program

Pipe Leakage and Protection

Security of supply relied not only on the performance of the pumps; the quality and protection of the delivery pipes was also found to be important. MAR schemes need to have contingency plans for coping with leaks in pipes at any stage in their operation. Another issue concerning the security of the pipe work was related to heavy vehicles driving over the pipes during work on other subterranean infrastructure. The experience in this project has demonstrated that MAR operators cannot expect that simply logging the pipe work location (via 'Dial Before You Dig') and placing signs (indicating the presence of the pipe work) will be sufficient to protect the pipe. Proactive measures through forward planning are essential.

Clogging of Galleries
Dealing with potential clogging of galleries during recharge is an issue that needs to be included in the operational plan of most MAR schemes (Dillon and Toze, 2005). As noted earlier, the presence of plant roots was a potential clogging issue for the gravel filled galleries. While plant roots would be very difficult to completely exclude from MAR systems, an understanding of the potential invasion of plant roots into MAR schemes and forward planning on ways to deal with this issue can help to overcome this problem. Also, designing MAR systems to be robust despite invasion of plant roots can be a means to overcome this problem.

Monitoring Equipment
Use of water level probes and sensors can be a valuable tool in monitoring the performance of MAR schemes. It was also noted in this project that while sensors and probes were valuable tools, they should not be solely relied upon. It was found that regular visual inspections of the MAR system considerably improved the performance of the infiltration galleries.

2.5. Conclusions from Infiltration Gallery Trials

The project demonstrated that treated wastewater can be efficiently and consistently recharged to the superficial aquifer in urban settings on the Swan Coastal Plain using infiltration galleries. In total, a volume of more than 36 ML was recharged to the aquifer at a rate of 50 KL per day over the three year life of the project. It found that a gravel-filled trench was not as effective or sustainable as the Atlantis Leach System® for infiltrating large quantities of secondary treated wastewater due to clogging with plant roots that occurred after one year of operation. A short-term experiment involving an increase in the inflow rate to the west (Atlantis Leach System®) gallery during the final two months of operating the Floreat site revealed no evidence of clogging with an average inflow rate of 60 L/min.

Various parameters were monitored and targeted experiments were done to gain a better understanding of the movement of the water through the unsaturated zone and the aquifer. The results obtained were used to model the movement of the recycled water through the MAR scheme. The modelling was able to predict the residence time within the aquifer but the level of heterogeneity within the aquifer and the highly transmissive nature of the aquifer meant that an absolute understanding the transport and residence of the water within the aquifer is still required. More research is needed on the characterisation of the aquifers at a local level at sites proposed for use as the location of MAR schemes.

The minimum residence time in the saturated zone at the Floreat site estimated using a three-dimensional MODFLOW-MODPATH simulation is 70 days $\pm$ 23 days between the galleries and the extraction bore. Due to the high rate of pumping from the extraction bore, dilution with background groundwater was of concern with regard to interpreting concentration reductions at specific monitoring bores down-gradient of the source. Based on a conservative transport model calibrated with chloride data, the estimated maximum dilution from background groundwater is 80% at the extraction bore, pumping at 250 KL/day (i.e. the recovered water consisted of 20% recharged water/80% groundwater).

Despite extensive sampling, enteric viruses or bacteriophage were not detected in the aquifer further than 1 metre from the infiltration galleries. Some periodic detection of thermotolerant coliforms and enterococci in water collected from various monitoring bores occurred; but, based on the studied decay rates of these microorganisms, it was considered that this is an artefact of the infiltration galleries being located on a sheep paddock and these microorganisms were sourced via surface contamination from sheep faeces, not from the recharged wastewater. In addition, T90 results for *Cryptosporidium*, adenovirus, rotavirus, coxsackievirus, bacteriophage MS2, *E. coli, S. typhimurium* and *E. faecalis* demonstrate that the aquifer has an active treatment capacity to remove pathogens during passage of recharge water through the aquifer. The highest T90 value was 56 days for adenovirus.

Removal of nutrients during passage through the unsaturated zone was assessed by comparing the concentrations in the gallery water with those in the groundwater sampled in adjacent monitoring bores. Significant declines in phosphate were observed; however, there was no evidence of attenuation or removal of nitrate due to the aerobic nature of the aquifer preventing denitrification from occurring. Concentration reductions in the pharmaceuticals carbamazepine and oxazepam, and to a lesser extent temazepam, were observed in monitoring bores down-gradient from the recharge source. Based on mass recovery rates, a field assessment of carbamazepine revealed no degradation, consistent with column study results. Using the ratio of oxazepam to conservative carbamazepine, there was no evidence to suggest biodegradation of oxazepam, although due to dilution, the measured concentrations were below detection level in the recovered water.

A series of issues relating to the operation and management of the infiltration galleries MAR schemes were observed and lessons were learnt from the occurrence of these issues. These issues related to factors such as the initial design and set up of the MAR schemes; understanding the reliability of the supply and the influence this may have on the day-to-day operation of the MAR scheme; the influence of dissolved iron on the quality of the recovered water; the appropriate installation and protection of the pipe system delivering the treated wastewater to the infiltration galleries; the clogging potential of the infiltration galleries and the appropriate management techniques if clogging occurs; and on the appropriateness of the monitoring equipment used to monitor the operation of the MAR schemes.

3. FATE OF TRACE ORGANICS USING LABORATORY COLUMN EXPERIMENTS

3.1. Aims and Objectives of Work Package

The objectives for this work have been clarified and focused to investigate, via large-scale column experiments, the fate of nine trace organics in two different aquifer materials to represent two managed aquifer recharge (MAR) options.

Below are the research objectives of the project:

- to investigate the fate and transport of selected trace organics considering the effect of pre-treatment level and aquifer type
- to determine the factors (e.g. adsorption, activity of groundwater microorganisms, redox potential, temperature) involved in removal of chemicals of concern during passage through the aquifer, through the use of laboratory columns
- to investigate the effectiveness of carbon dosing for nitrogen removal in laboratory conditions using filtered secondary treated wastewater and Spearwood sands
- to assess chemicals of concern in aquifer recharge using reverse osmosis (RO) treated wastewater
- to geochemically model contaminant fate and transport during aquifer recharge of RO treated wastewater.

The main results from this component of the project are summarised below. Details of the methodology and more results concerning the fate of trace organics using laboratory column experiments are presented in the complete final report of this project.

3.2. Laboratory column experiments

Four different groups of trace organics, previously identified in recycled water were investigated via large-scale column experiments over a 12-month period. The trace organic groups were endocrine disrupting chemicals (EDCs) (17β-estradiol, 17α-ethynylestradiol and bisphenol A); pharmaceutical products (oxazipam and carbamazepine); disinfection by-products (N-nitrosodimethylamine and N-nitrosomorpholine); and x-ray contrast media compounds (iohexol and iodipamide).

Two different options for managed aquifer recharge were simulated, a deep injection option and a shallow injection option. The deep injection MAR option was simulated by injecting tertiary treated recycled water (recycled water from the Beenyup microfiltration/reverse osmosis (RO) pilot plant) into anaerobic Leederville sediment from the Leederville aquifer. The shallow injection MAR option was simulated by injecting secondary treated recycled water (recycled water from the Subiaco Wastewater Treatment Plant subjected to rapid sand filtration as used at the Floreat Infiltration Gallery site) into aerobic Spearwood sediment from the Tamala aquifer. A summary of the different combinations of sediment and influent water and sterility conditions used in the columns is given in Table 11. The stainless steel columns were 2 m in height with an internal diameter of 14.5 cm (Figure 12).

The behaviour and persistence of each trace organic under the different redox conditions and water types in the Leederville and Spearwood sediments were assessed based on their chemical retardation coefficient (R) and degradation half-life, determined from the experimental data. Details of the sampling and analytical methods are given in the complete report of the project.

Table 11. Summary of the different sediment/influent water combinations used in the large-scale column experiments

Column	Sediment	Influent water	Sterility
A	non-washed Leederville	recycled Beenyup water	non-sterile
B	non-washed Leederville	recycled Beenyup water	sterile
C	Spearwood	recycled Floreat infiltration gallery water	non-sterile
D	Spearwood	recycled Floreat infiltration gallery water	sterile
E	washed Leederville*	recycled Beenyup water	non-sterile
F	washed Leederville*	recycled Beenyup water	sterile

* Attempts to sufficiently oxidise these sediments were unsuccessful and the columns were subsequently used as duplicate Leederville sediment columns.

Figure 12. Large columns installed in the CSIRO laboratory. Photograph by author.

3.3. Outcomes and Results

3.3.1. Sediment Properties

Sediment porosities of the Leederville and Spearwood sediments were determined using bromide tracer tests conducted during the column experiment. Hydraulic conductivity (*K*) was determined based on the difference in piezometric head measured using small piezometer tubes located at selected ports along each column. Other sediment properties were determined on sediment sub-samples. Details of the sediment properties are given in Table 12.

Table 12. Sediment properties

Column	Sediment	Bulk density (g/cm^3)	TOC* % (w/w)	Pyrite % (w/w)	Porosity (-)	Hydraulic conductivity (m/d)
A	non-washed Leederville	1.51	1.1	0.62	0.39 ± 0.06	0.32 ± 0.01
B	non-washed Leederville	1.51	1.1	0.62	0.34 ± 0.05	0.07 ± 0.01
C	Spearwood	1.66	0.02	-	0.48 ± 0.05	12 ± 6
D	Spearwood	1.66	0.02	-	0.45 ± 0.05	23 ±12
E	washed Leederville	1.51	0.32	0.71	0.37 ± 0.03	10 ± 8
F	washed Leederville	1.51	0.32	0.71	0.46 ± 0.12	7.2 ±1.3

* TOC = total organic carbon.

The difference in hydraulic conductivities between the non-washed Leederville sediment (columns A and B), and washed Leederville sediment (columns E and F) could be attributed to the difference in sediment preparation. Sediment used in columns E and F was washed prior to packing to remove drilling mud. As a result finer silty material was removed as the excess water was decanted off prior to packing.

3.3.2. Sorption of Trace Organics to Leederville and Spearwood Sediments

Sorption of trace organics can occur through hydrophobic attraction between sediment organic matter and non-polar organic contaminants (hydrophobic partitioning), or through the attraction of compounds to mineral surfaces by electrostatic forces (physical sorption). Therefore, the extent to which a trace organic will sorb is dependent on the compound's structure and the organic carbon content of the sediment and/or the minerals present in the sediment.

The 50% breakthrough distance for each trace organic compared to the 50% breakthrough distance for the tracer bromide was used to determine retardation coefficients (R) of the trace organics. Retardation coefficient (R) values for the trace organics calculated for the Leederville and Spearwood sediment are shown in Table 13.

Table 13. Octanol/water partitioning coefficients (K_{ow}) and retardation coefficients (R) of trace organics in Leederville and Spearwood sediments. Errors are standard errors.

Trace organic		Log K_{ow}	Retardation coefficient (R)	
			Leederville sediment (column F)	Spearwood sediment (column D)
17β-estradiol	E2	3.9	53 ± 10	-
17α-ethynylestradiol	EE2	4.1	67 ± 9	1.1 ± 0.2
bisphenol A	BPA	3.6	18 ± 4	1.1 ± 0.2
Oxazepam	OXAZ	2.3	41± 2	1.0 ± 0.2
Carbamazepine	CARB	2.3	13 ± 1	1.0 ± 0.2
N-nitrosodimethylamine	NDMA	0.64	1.1 ± 0.2	1.0 ± 0.2
N-nitrosomorpholine	NMOR	0.43	1.2 ± 0.2	1.0 ± 0.2
Iohexol	IOX	2.8	2.6 ± 0.4	1.0 ± 0.2
Iodipamide	IDP	5.2	19 ± 3	1.0 ± 0.2

The low R values of the trace organics determined for the Spearwood sediment would be consistent with limited hydrophobic partitioning as a result of the low organic carbon content of the Spearwood sediment (0.02% w/w). Also, this data suggests there is little physical sorption due to attraction of the trace organics to minerals surfaces by electrostatic forces. In contrast, in the relatively high organic carbon content Leederville sediment, all the trace organics tested except the nitrosamines and IOX showed substantial sorption to the aquifer material. This suggests that these trace organics would have slow migration rates in the Leederville aquifer

3.3.3. Trace Organic Biodegradation

Degradation half-life curves were fitted to the trace organic data and calculated biodegradation half-lives for the trace organics are given in Table 14.

Table 14. Half-life data for all trace organics in Leederville and Spearwood sediments

Trace organic	Half-life (days)			
	Leederville sediment		Spearwood sediment*	
	Non-sterile (column E)	Sterile (column F)	Non-sterile column (C)	Sterile (column D)
E2	6	50	<1	<1
EE2	25	>100	74	>100
BPA	<1	>100	<1	<1
OXAZ	>100	>100	>100	>100
CARB	>100	>100	>100	>100
NDMA	>100	>100	>100	>100
NMOR	>100	>100	>100	>100
IOX	>100	>100	<1	>100
IDP	2	>100	>100	>100

* prior to the trace organics entering the ethanol amended zone of the column

In the non-sterile Spearwood sediment, degradation of E2, EE2, BPA and IOX was observed; however the other trace organics tested were not degraded. Therefore, concentrations of the nitrosamines (NDMA and NMOR), pharmaceuticals (OXAZ and CARB), and the x-ray contrast medium (IDP) were determined unlikely to be substantially reduced during MAR under these aquifer conditions. Rapid degradation of E2, EE2, BPA and IDP were observed in the columns containing the non-sterile Leederville aquifer material; however, none of the other trace organics were degraded. Therefore, in the Leederville aquifer, concentrations of the nitrosamines, pharmaceuticals, and IOX are unlikely to be reduced substantially during aquifer passage associated with MAR.

3.3.4. Geochemical Changes

The injection of aerobic RO water into the Leederville sediment columns promoted a range of geochemical changes. Low nitrate concentrations in the influent RO water were observed to decrease in the non-sterile Leederville columns, but persisted in the sterilised Leederville columns. Based on this data, a denitrification half-life of 2.1 days was estimated for the Leederville sediment. The denitrification within the non-sterile Leederville column provides good evidence of on-going biological activity in the Leederville sediment.

Influent dissolved oxygen concentrations (~7 mg/L) were rapidly reduced in all Leederville sediment (e.g. Figure 13) columns to below detection (<0.5 mg/L), suggesting abiotic and possibly biotic (for the non-sterile sediment) oxygen-consuming processes, such as pyrite oxidation. The increase in sulphate concentrations further down-gradient could be attributed to mechanisms other than pyrite oxidation, such as mineral dissolution.

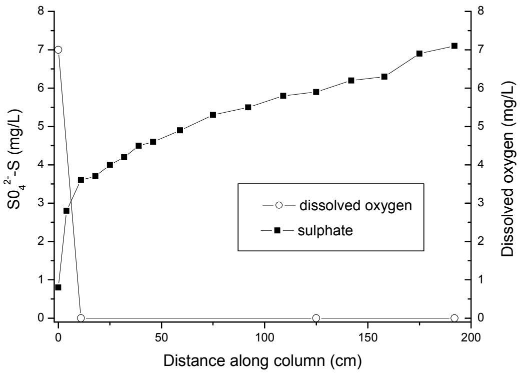

Figure 13. Sulphate and dissolved oxygen concentrations in the non-sterile Leederville column (column E) after 56 days of recycle water addition

Increases in a range of cations (K^+, Mg^{2+}, Ca^{2+}, Fe^{2+}) and other anions (HCO_3^{2-}) were also observed along both the sterile and non-sterile Leederville columns (e.g. see Figure 14). However, Na^+ and Cl^- concentrations along the Leederville columns remained consistently low. The increases in these cations and anions suggest mineral dissolution of the Leederville sediment may be occurring. Possible dissolution of gypsum ($CaSO_4 \cdot 2H_2O$) and dolomite ($CaMg(CO_3)_2$)/ankerite ($Ca_2MgFe(CO_3)_4$) may explain the increases in cations and anions. Based on XRD analysis, the Leederville sediment contained 0.2% (w/w) gypsum and 0.1% (w/w) dolomite/ankerite. Johnson et al. (1998) found that the injection of RO water into sediment-filled columns caused aggressive dissolution of carbonate minerals. No increase in heavy metal(loid)s (Cd, Co, Cr, Cu, Mo, Ni, Pb, Zn, As) or Cl^- was observed along the length of the Leederville sediment columns.

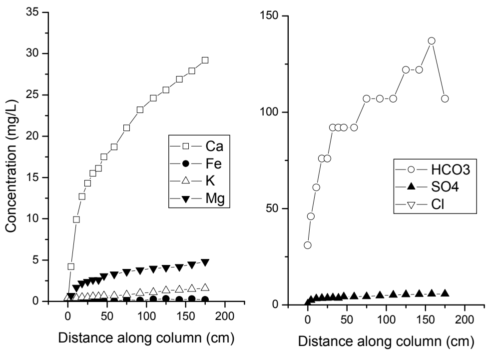

Figure 14. Selected cation (K^+, Mg^{2+}, Ca^{2+}, $Fe2^+$) and anion (HCO_3^{2-}) concentrations along the non-sterile Leederville column (column E) after 56 days of recycle water addition

No substantial geochemical changes were observed along the length of the Spearwood sediment columns as a result of the injection of aerobic secondary treated recycled water. Nitrate concentrations persisted along the length of both sterile and non-sterile columns and cation/anion concentrations were relatively stable.

3.3.5. Carbon Dosing of the Spearwood Sediment Columns

To investigate the effectiveness of carbon dosing for nitrogen removal in secondary treated wastewater, ethanol was delivered via diffusion through a polymer mat to each of the Spearwood sediment columns. Within 7 days of ethanol delivery, nitrate concentration decreased substantially down-gradient of the polymer mat in the non-sterile Spearwood sediment column (column C). Later, denitrification was also observed up to 40 cm up-gradient of the ethanol delivery location (Figure 15), probably due to back diffusion of ethanol as a result of the low water flow rates used in the column experiment. No denitrification was observed in the sterile Spearwood sediment column (column D).

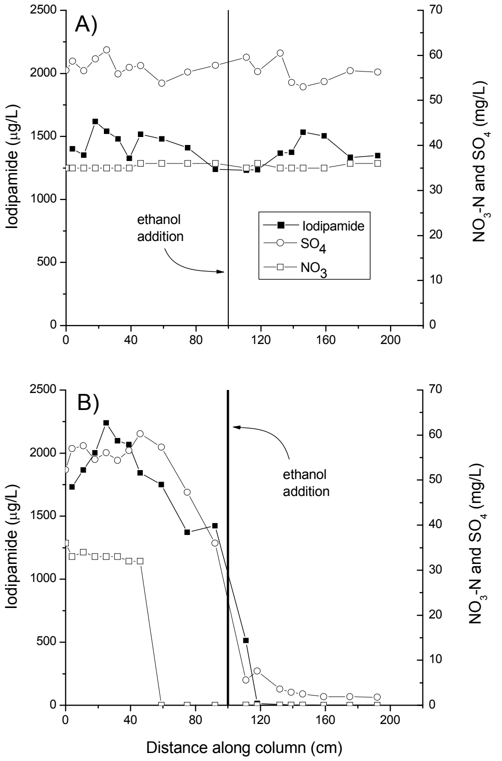

Figure 15. Comparison of nitrate, sulphate and iodipamide concentrations along A) the sterile (column D) and B) non-sterile (column C) Spearwood sediment columns, during the period of ethanol delivery

From the nitrate and sulphate concentrations (Figure 15), a denitrification half-life of 1.9 days, and a sulphate reduction half-life of 2.0 days was estimated. These results suggest that carbon dosing, using ethanol, promoted biological removal of nitrate and sulphate in the secondary treated wastewater. Therefore, this carbon dosing technique could provide a remediation option to remove high concentrations of nitrate from secondary treated wastewater during aquifer passage. Also, the reducing conditions promoted via ethanol addition, resulted in enhanced degradation of iodipamide with a half life of 3 days (Figure 15).

3.4. Conclusions from Laboratory Column Experiments

Large-scale column experiments were conducted over a period of 12 months to investigate the fate of nine trace organic chemicals under different aquifer redox conditions. Experiments were conducted to simulate (i) a deep injection MAR option involving the injection of tertiary treated (including reverse osmosis) recycled water into the anaerobic Leederville aquifer, and (ii) a shallow injection MAR option involving the injection of secondary treated recycled water into the aerobic Tamala aquifer containing Spearwood sediment. The shallow injection MAR option experiment was undertaken to provide comparable in-lab data to the field Floreat Infiltration Gallery field experiment.

In the relatively high organic carbon content Leederville sediment, all trace organics except the nitrosamines and iohexol showed substantial sorption to the aquifer material (R = 13 to 67), suggesting slow migration rates of these trace organics in the Leederville aquifer. Rapid degradation of E2, EE2, BPA and iodipamide (half-lives <1 to 25 days) were observed, however, the other trace organics were not degraded (half-lives >100 days). Therefore, nitrosamines, pharmaceuticals, and iohexol concentrations in injected treated wastewater are unlikely to be reduced substantially during aquifer passage associated with MAR in the short term.

In the low organic carbon content Spearwood sediment, all trace organics were not retarded with R values between 1.0 and 1.1, indicating that these compounds would travel at near groundwater velocities in the Tamala aquifer. Degradation of E2, EE2, BPA and iohexol (half-lives <1 to 74 days) was observed, however, the other trace organics were not degraded (half-lives >100 days). Therefore, nitrosamines, pharmaceuticals, and iodipamide concentrations in injected treated wastewater are unlikely to be reduced substantially during aquifer passage associated with MAR.

Geochemical changes as a result of the injection of aerobic RO water into the Leederville sediment were observed. These changes included (i) rapid oxygen consumption with the production of sulphate, suggesting pyrite oxidation; and (ii) increases in selected anions and cations suggesting mineral dissolution of possibly gypsum, dolomite and ankerite. However no increase in heavy metal(loids) concentration in the column water was observed.

Removal of nitrate from secondary treated wastewater during aquifer passage was demonstrated in large-scale columns using ethanol carbon-dosing. Using this technique, denitrification half-lives of 1.9 days were observed. Additionally, the reducing conditions promoted via ethanol addition, resulted in enhanced degradation of iodipamide.

4. COMMUNITY ATTITUDE AND BEHAVIOUR RESEARCH

4.1. Introduction to Work Package

While advancements in treatment processes have broadened the range of potential uses and sources of recycled water, the successful implementation of any reuse scheme hinges on public acceptance. As an option for responsible water resource management, water reuse is widely promoted by the Australian community. However, reactions from people when it comes to actually using the water are frequently quite different, as has been shown in the 2006 referendum in Toowoomba, Queensland. Water recycling is seen to be a logical and necessary inclusion in the range of water resource management options, but communities frequently feel a reluctance to use the water where close personal contact occurs. Until recently little has been known of how people make their decisions to accept different water recycling schemes for a range of different uses. What was apparent was that many technically sound reuse schemes around the world have failed because communities have rejected them, often at the eleventh hour (Po et al., 2004).

A three-year systematic social research program was undertaken to identify people's perceptions, attitudes and intended behaviour towards MAR for a range of fit-for-purpose uses. Further, the information provides strategies for ongoing engagement with the broader community for decision- and policy-makers to optimise successful implementation of future water supply schemes incorporating MAR.

The main results from this component of the project are summarised below. Details of the methodology and more results concerning the community attitude and behaviour research are presented in the complete final report of this project.

4.2. Stage 1 – Predicting Community Behaviour

A previously refined predictive behavioural model incorporating a range of psycho-sociological variables was tested (see Figure 116). The variables in the model were hypothesised to have significant influence over people's decisions to act favourably or otherwise towards recycled water schemes. A scenario outlining an MAR scheme for indirect potable reuse in metropolitan Perth, Western Australia, was administered via telephone survey to 500 randomly selected Perth householders.

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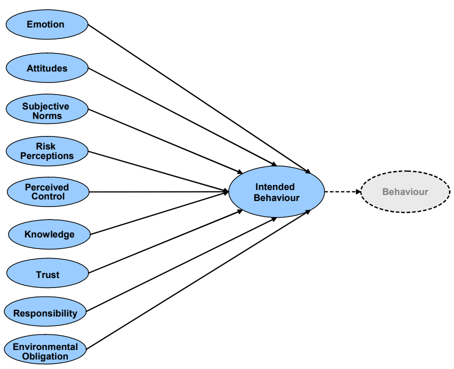

Figure 16. Original hypothesised model of intended behaviour

The survey found that, while over half of respondents intended to support an MAR scheme in Perth, a large proportion expressed moderate and qualified responses in relation to intended behaviour towards the scheme. Roughly one-quarter of respondents gave responses that indicated refusal to support the scheme. Further, almost 20% of respondents who had answered ‘yes’ when asked if they would drink water from the scheme also expressed unprompted reservations and qualifications regarding the scheme later in the questionnaire (e.g. ‘need more information’, ‘there are less risky alternatives’, ‘only if absolutely safe’).

While there were no statistically significant differences based on education levels, income levels, family unit and age, males’ behavioural intentions toward the scheme were significantly more positive than females. Providing appropriate opportunities to encourage the engagement of women in a community involvement program and addressing their concerns should therefore be a priority in the ongoing planning of an MAR scheme.

In relation to other schemes over the proposed MAR scheme, more people appeared to prefer a desalination scheme but fewer people preferred the option of taking water from the South West Yarragadee. In both these instances however, a large proportion of respondents were unsure of which they would prefer. This perhaps suggests that a sizeable proportion of those who state support for an MAR scheme do so largely because it represents a positive action in relation to water reuse, but are not convinced it is the best or most agreeable option for water augmentation in Perth.

Modelling Support

The results of structural equation modelling replicated the major findings of a preliminary study (Leviston et al., 2006a). Among a group of variables, emotion and subjective norm were found to have the strongest direct influence on intended behaviour. Fairness, trust, and perceived health and system risks also had significant influences. Knowledge about wastewater and the use of MAR failed to contribute significantly to the prediction of intended behaviour. The model was extremely strong in its predictive power, able to account for 82% of the variance in intended behaviour scores (see Figure 1717).

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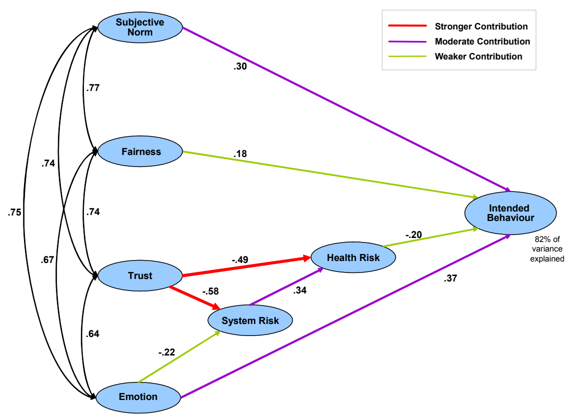

Figure 17. Simplified overall structural equation model. The numbers in the diagram refer to the correlation coefficients between variables, which can range from -1 – a strong *negative* relationship – to +1 – a strong *positive* relationship.

The Role of Risk
The importance of risk became more apparent when it was modelled in isolation, accounting for 69% of the total variance in intended behaviour. Of the three types of risk investigated (environmental, system and human), risk to human health had the most bearing on people's intentions toward the scheme. The strong influence of risk here may be somewhat surprising considering its role in the overall model, but correlations between risk, trust and variables like emotion and subjective norm suggest that its direct influences on intended behaviour are belied by its strong relationships with the other variables.

With regards to environmental risk, the issue of aquifer health appears to be a 'sleeper', but should not be underestimated as the debate continues and people learn more about what is in wastewater. It was apparent that people considered the scheme to be unfair to the aquifer, and even some of the subjective norm measures showed some indication of concern for the aquifer. Thus, while authorities and scientists are currently promoting the injection of wastewater into the aquifer to assist long-term sustainability, concern about foreign materials going into the aquifer has the potential to be a significant future issue for the community.

System risk did not significantly predict intended behaviour directly, but it was found to be a significant determiner of both environmental risk and health risk. It can therefore be reasoned that if people become more convinced that the implementation, monitoring and maintenance of the scheme is low-risk, they will be less inclined to feel that the scheme poses a risk to their own health or that of the environment.

The Role of Fairness
Consistent with previous research concerning the role of fairness in decision-making processes about water supply systems (Leviston et al., 2006b), this study suggests that people's judgement of whether a recycled water scheme is fair or not significantly contributes to their intended behaviour in support (or protest) of the scheme. The measures here involved overall fairness judgements, as well as fairness to different groups in the community and to the aquifer itself. This is an important finding for organisations interested in gaining support for recycling schemes. Should only certain sections of the Perth community be required to drink from the MAR scheme, the issue of fairness may play a central role in any debate.

4.3. Stage 2 – Technical and Community Perceptions of Risk

The second stage of the MAR social research program involved a series of scoping focus groups, workshops and interviews with both technical experts working in the MAR field and general community members. While exploratory in nature, the content of these focus groups was structured upon the findings from Stage 1 of the research program. In response to the scoping activities, a Q-Method research methodology was implemented. This research methodology engaged an innovative technique to explore, in greater detail, (i) community perceptions of risk for different fit-for-purpose uses, (ii) technical expert perceptions of risk, and (iii) technical expert perceptions of community perceptions of risk.

In Q-Method, issues are captured using a diverse range of statements which participants are then asked to sort and rank on a continuum (called Q-sorts) – from most unlike to most like their points of view. Q-sorts relating to indirect potable water, horticultural irrigation and public open space MAR schemes were administered to 37 community members from the northern suburbs of Perth[2], while 20 technical stakeholders and water professionals completed an indirect potable water MAR scheme Q-sort. Technical and professional groups

[2] An indirect potable MAR scheme would principally supply the northern suburbs of Perth

were also required to complete the indirect potable water Q-sort from the perspective of a 'typical' community member.

The analysis supported previous research undertaken by the Australian Research Centre for Water in Society (ARCWIS) that the specific fit-for-purpose use of the water informs the decision-making framework. That is, different typologies of decision-making emerged for each of the different fit-for-purpose uses, indicating that people use different criteria on which to base their decisions for each water use activity. An analysis of the community Q-sorts revealed a high level of heterogeneity. This was in contrast to the technical perceptions of the community, which revealed a much higher level of homogeneity in perceived community opinion.

4.4. Implications for Planning

Dealing with Trust, Risk and Uncertainty

Some factors, such as a person's emotional reaction to a recycled water scheme, may be deeply entrenched while factors such as perceptions of risk or organisational trust are potentially more flexible and receptive to change. The high correlations between risk, trust and other variables found in the stage one behavioural modelling suggest that if one is able to exert change in people's risk and trust perceptions, one by consequence might promote change in variables otherwise less receptive to change. Our research suggests that building trust in key organisations has the potential to temper emotional responses. Trust-building in turn is affected by other factors that the community expresses concern over, such as transparency in legislative arrangements.

Many findings support the concept that people's conceptualisation of risk in relation to schemes involving wastewater is dependent on end-use (e.g. Po et al., 2005). Consequently, risk perceptions and methods of addressing them are probably best tailored specifically to the intended end-use. That is, the communication approach would differ for horticultural schemes and public-open-space irrigation, while indirect potable use schemes would address different concerns again. The impact of unknown risks on community decision-making is a key element for policy makers to address.

Presenting in Context – the Importance of Alternatives and Complexity

The findings reinforce the importance of presenting new water augmentation options in combination with the range of other steps that will be taken. That is, rather than presenting an augmentation option in isolation, it should be expressed and presented in the context of a 'holistic' strategy toward water security. Presenting a water augmentation option such as MAR in the context of other options may have an additional influence for mitigating risk perception. Highlighting the planning complexity of water sustainability to the community may 'water down' the risks of MAR by bringing into play the risks associated with other water management options, including the option of not doing enough to secure a long-term, sustainable water supply for Western Australia.

The perspective that complexity of a water augmentation strategy needs to be highlighted to the community to ameliorate risk perception is supported both by the Q-sorts and by the focus groups which guided the development of Stage 2. Rather than a blatant refusal of acceptance of an indirect potable reuse scheme that emerged, a dislike of reuse in the face of competing options emerged. Furthermore, allowing people to make decisions about MAR in context with their decisions about other water augmentation options would ultimately provide a set of community responses and attitudes that was more consistent with a Western Australian water policy context.

Transparency in Regulation
Both Stage 1 and Stage 2 of the research program highlighted the importance of the need for transparent political, legal and scientific processes. This was important for nearly every factor that emerged in the Q-Method analysis, not just for those who agreed with the particular MAR scheme, or for those who disagreed with it. These concerns were inextricably linked with trust in the organisations charged with running and regulating augmentation schemes, especially one involving perceived risks to human health.

Community Inclusion – Beyond the 'Yuck Factor'
The notable omission of the 'yuck factor' as the prominent concern for community is perhaps an example of the limitations of ascribing questions rather than having them generated in the process of deliberative debate. It is proposed here that focusing solely on emotive aspects of community decision making is to underestimate the complexity of community opinion, and effectively reduce planners and researchers' ability to respond to actual community concerns and debates. Considered the staple cause of rejection of schemes involving recycled wastewater, the community appears as a whole to have moved beyond a 'toilet to tap' mentality to a more complex conceptualisation of the issue. Scientific and decision making communities need to be open and responsive to new and increasingly multifaceted concerns that comprise the new arena of concerns.

4.5. Conclusions from Community Attitude and Behaviour Research

The research indicates that, while the concept of an indirect potable scheme using MAR would gain support from the majority of the community, there are a number of key barriers to social acceptance that must be overcome to ensure its successful implementation. The roles of emotion and subjective norms, along with issues of fairness, institutional trust, and perceived health and system risks associated with the scheme, are all significant determinants of how a scheme will be received by the broader community.

Further, the investigation into decision-making frameworks for dealing with perceived risks indicates that community decision-making frameworks in relation to MAR are complex and heterogeneous, both between individuals and between different fit-for-purpose uses. This is compounded by the finding suggesting that technical perceptions of what factors the 'community' bases its decisions on are weakly correlated with the actual drivers of decision-making for most individual members of the community.

To address these issues it is suggested that, rather than pursuing a one-size-fits-all approach to public engagement, different engagement techniques are utilised for resolving different issues relating to the public acceptance of MAR, and that by using a variety of strategies concurrently, outcomes for both the community and future water security will be optimised.

5. HEALTH RISK ASSESSMENT

5.1. Aims and Objectives of Work Package

The aim of the work package was to assess the human health risks due to micro-organisms and trace chemical contaminants found in recycled water delivered via managed aquifer recharge (MAR). This risk assessment is only considering MAR for non-potable uses, e.g. irrigation. However, the chemical screening risk assessment uses drinking water guidelines to allow a conservative comparison of chemicals, in the absence of any other health-based chemical guidelines.

The objectives of the work package were the identification and quantification of chemical and microbiological health risks associated with the use of recycled water and MAR and an assessment of appropriate management practices to minimise these risks. This objective included the following:

- to develop a risk assessment of selected microbial and chemical contaminants in treated wastewater
- to undertake a quantitative microbial risk assessment of water recycled through MAR
- to undertake a screening health risk assessment of trace chemical contaminants in secondary treated wastewater (source water)
- to develop a risk assessment for significant chemical contaminants in water recycled through MAR.

The main results from this component of the project are summarised below. Details of the methodology and more results concerning the health risk assessment of MAR are presented in the complete final report of this project.

5.2. Recycled Water Health Risk Assessment

An initial assessment determined that while both microbial and chemical contaminants are the main public health concerns when considering any application for the reuse of recycled water, in the case of irrigation applications using water recovered from an MAR scheme, microbial hazards are the major concern.

Determination of microbial exposure was based on the principles of risk assessment using Quantitative Microbial Risk Assessment (QMRA). This well-validated approach considers the estimate of consequences from a planned or actual exposure to infectious microorganisms.

Determination of chemical risk was based on a screening human health risk assessment (SHRA). The only health-based chemical guidelines available are for drinking water purposes. Lower exposure to recycled water through irrigation is unlikely to result in any significant risk to human health from chemicals; however, the risk quotient approach (RQ) using drinking water guidelines allows comparison of risk associated with different chemicals. Chemical contaminants are of concern only where recycled water is used for drinking purposes.

Water quality assessment was conducted for: Subiaco Wastewater Treatment Plant secondary treated wastewater (‘Subiaco wastewater’); recycled water entering the Floreat Infiltration Galleries; and water from the aquifer down-gradient of the galleries; and through column experiments (see earlier section on the fate of trace organics using laboratory column experiments).

5.3. Quantitative Microbial Risk Assessment

Quantitative microbial risk assessment (QMRA) of water recycling and MAR systems requires the quantification of pathogen occurrence in source water and their removal through various treatment barriers. When pathogen occurrence is combined with exposure scenarios and pathogen dose-response relationships, the risk to human health can be estimated.

The end point of the human health risk assessment used in this report was expressed as Disability Adjusted Life Years (DALYs). DALYs have been used extensively by agencies such as the World Health Organization (WHO) to assess disease burdens and to identify intervention priorities associated with a broad range of environmental hazards (WHO, 2004). For example, one DALY per million people a year roughly equates to one cancer death per 100 000 in a 70 year lifetime, a benchmark often used in chemical risk assessments (WHO, 2004). The DALY is calculated as the product of the probability of each illness outcome with a severity factor and the duration (years). The advantage of using DALYs over an infection risk end point is that it not only reflects the effects of acute end-points (e.g. diarrhoeal illness) but also the likelihood and severity of more serious disease outcomes (e.g. Guillain-Barré syndrome associated with *Campylobacter*).

The hypothesis to be tested was that risk attributable to using water from the Floreat Infiltration Galleries for irrigation of public open spaces resulted in a disease burden of 1×10^{-6} DALYs per year or less.

Hazard identification

The scope of the assessment was limited to three reference pathogens, which act as surrogates for the three main microbiological groups: bacteria (*Campylobacter*), protozoa (*Cryptosporidium parvum*) and viruses (rotavirus). These pathogens were selected as they are known to be present in secondary treated wastewater and contribute the greatest population health burden in terms of DALYs (NRMMC-EPHC, 2006).

Dose-response

Information on relationships between doses of pathogens and incidence or likelihood of illness is generally obtained from investigations of outbreaks or from experimental human-feeding studies (WHO, 2004). The ingestion dose-response models and the DALYs per infection used in this report for the hazards identified above are extensively detailed in WHO (2004) and NRMMC-EPHC (2006).

Exposure assessment

The main route of exposure to microbial hazards is ingestion, including ingestion of droplets produced by sprays, garden irrigation and accidental intake. The three exposure scenarios of the extracted Floreat Infiltration Galleries water were assessed in this report. The point estimate exposure volumes and frequencies of exposures per person are provided in Table 15 (NRMMC-EPHC, 2006). In assessing the risk to human health, each of the three index pathogens was assessed for each of the three scenarios.

Table 15. Irrigation exposure scenarios assessed

Scenario	Frequency of exposure (n/yr)	Exposure volume (mL)
Ingestion of sprays	90	0.1
Garden irrigation	90	1
Accidental ingestion	1	100

Risk characterisation
The last step in risk assessment is to integrate information from hazard identification, dose-response and exposure assessment, to determine the magnitude of risk. In all cases, the variables in determining the magnitude of risk for the reference pathogens are counts of the organisms and exposure.

Conceptual model
The conceptual model underpinning this risk assessment assumes that pathogens contained in secondary treated effluent from Subiaco Wastewater Treatment Plant are infiltrated into the Floreat Infiltration Galleries at a steady rate for an average of 4 days. The recharged effluent then remains in the subsurface for an average of 70 days prior to recovery from a bore and used for irrigation of public green spaces. There is assumed to be no filtration of pathogens during passage through the aquifer, only decay. Similarly, there is no mixing of the reclaimed water with native groundwater (dilution).

This model used pathogen occurrence data in treated wastewater from the scientific literature, decay data from the *in situ* experiments at the infiltration gallery site, the hydrologeological assessment of residence times in the aquifer, and a number of different exposure scenarios involving irrigation to determine the risk to human health.

5.3.1. QMRA Results

In most scenarios the mean risk to human health posed by rotavirus was greater than that of *Cryptosporidium*, which in turn was greater than that of *Campylobacter* (Table 16). The mean human health risks arising from the ingestion of sprays and accidental ingestion scenarios from *Campylobacter* and *Cryptosporidium* were acceptable (<1.0 $\times$ 10^{-6} DALYs) whereas the risk from rotavirus was unacceptable. For the garden irrigation scenario the risks were unacceptable for rotavirus and *Campylobacter*. The median value is seen as a better indication of the central tendency of the risk characterisation results in Table 16. For the median human health risk, only rotavirus was of an unacceptable risk.

Table 16. Risk characterisation Results for three exposure scenarios (DALYs)

	Ingestion of sprays		
Pathogen	Mean	Median	95^{th} percentile
Campylobacter	4.6×10^{-7}	$<1.0 \times 10^{-10}$	$<1.0 \times 10^{-10}$
Cryptosporidium	6.2×10^{-8}	1.6×10^{-8}	2.5×10^{-7}
Rotavirus	**4.3×10^{-6}**	**4.9×10^{-7}**	**7.0×10^{-4}**
	Garden irrigation		
Pathogen	Mean	Median	95^{th} percentile
Campylobacter	**1.5×10^{-6}**	$<1.0 \times 10^{-10}$	$<1.0 \times 10^{-10}$
Cryptosporidium	6.2×10^{-7}	1.6×10^{-7}	**2.5×10^{-6}**
Rotavirus	**2.8×10^{-5}**	**4.0×10^{-6}**	**1.4×10^{-4}**
	Accidental ingestion		
Pathogen	Mean	Median	95^{th} percentile
Campylobacter	1.2×10^{-7}	$<1.0 \times 10^{-10}$	$<1.0 \times 10^{-10}$
Cryptosporidium	6.8×10^{-7}	1.8×10^{-7}	**2.8×10^{-6}**
Rotavirus	**4.2×10^{-5}**	**3.9×10^{-6}**	**1.6×10^{-4}**

Values which exceed the upper limit of 10^{-6} DALYs per person per year are shown in bold.

As far as it was possible to determine, the average annualised risk was greater than 10^{-5} DALYs per person per year for all scenarios for at least one pathogen. The issue of whether management intervention is required would depend on how risk averse the exposed community and supply manager were and how much of a safety margin they desired.

Sensitivity analysis

QMRA coupled with stochastic Monte Carlo simulations can provide a sensitivity analysis of the factors that most significantly influence risk, i.e. those factors which are highly correlated with increased or decreased risk. This analysis helps prioritise risk management efforts and for subsequent improvement of the QMRA model by focusing investigation priorities. Figure 18 shows a representative tornado diagram calculated for the highest risk scenario: rotavirus exposure through accidental ingestion.

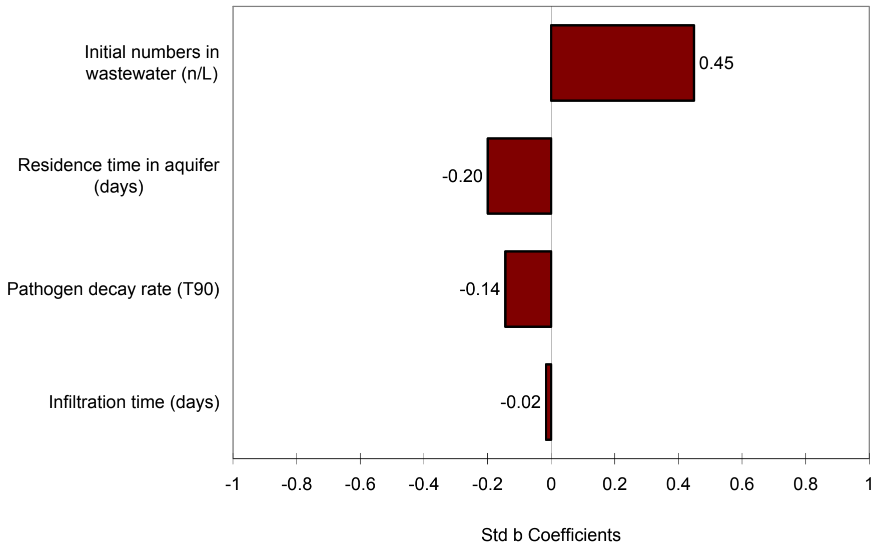

Figure 18. Sensitivity analysis for rotavirus accidental ingestion scenario

Residence time was the single most influential negatively correlated factor. Expanding this relationship it was found that to obtain a mean risk for each of the scenarios that was below the guideline value ($<1\times10^{-6}$ DALYs), the residence time in the aquifer would need to be ~150 days; longer than the 70 days of the model.

5.4. Trace Chemical Contaminants

Many chemical contaminants (both inorganic and organic) found in wastewater have guideline values which indicate the acceptable level if found in a drinking water supply. The term ‘Trace Organics’ more specifically refers to a range of emerging chemicals, such as: pharmaceuticals, endocrine disrupters, disinfection by-products and flame retardants. These emerging contaminants pose a challenge to public health regulation as in many cases there is no toxicological data or guideline value from which to derive the potential risk to human health.

Therefore, to evaluate the potential health risks of trace chemical contaminants in recycled water from MAR, a screening health risk assessment (SHRA) was developed. This SHRA is a systematic desktop assessment of potential adverse health effects of pollutants at the concentrations observed in the recycled water assuming that that water were available for drinking. The assessment requires the quantification of trace chemical contaminants in the secondary wastewater (source water) and their removal through the infiltration galleries. Full details on the methodology are shown in the complete final report for the project.

Risk quotients (RQs) are the most widely used method of assessing risk from trace chemical contaminants by comparing the measured chemical concentrations with health values. Health values are concentrations below which no adverse health effects are expected if the water is consumed over a lifetime. The health values are calculated assuming an average daily intake of 2 litres of water for an individual with a 70kg body weight over 70 years of water consumption.

The quantification of the screening human health risk assessment used in this report is expressed as a screening RQ for each one of the chemicals under analysis. Screening RQs below 1 are considered of low health significance. Screening RQs above 1 indicate that more data on occurrence and fate and therefore, a complete health risk assessment, is required.

5.4.1. SHRA Results

Subiaco wastewater characterisation

Of the 355 chemicals tested for, 88 were detected in at least one of the four samples taken from the Subiaco wastewater. The list of chemical groups analysed for include a broad range of chemical groups with different physico-chemical characteristics and toxic effects (Table 17). All trihalomethanes (THMs), complexing agents and gross alpha and gross beta particle activity analytes tested for were detected in the Subiaco wastewater.

Table 17. Total number of chemicals analysed for in Subiaco wastewater and the percentage of detections

Parameter	n	Detected (%)	Parameter	n	Detected (%)
DBPs			Volatile Organic Compounds (VOCs)	59	13.6
Trihalomethanes (THMs)	6	100	Polycyclic aromatic hydrocarbons (PAHs)	17	29.4
Haloacetic acids (HAAs)	9	44.4	Dioxin and Furans	17	5.9
Haloacetonitriles	6	16.7	Polychlorinated biphenyls (PCBs)	12	16.7
Haloaldehydes	6	16.7	Gross alpha and gross beta particle activity	2	100
Haloketones	4	50	Hormones	4	25
Chloropicrin	1	0	Complexing agents	4	100
N-Nitrosamines	9	88.9	Anions	3	
Pharmaceuticals			Other chemicals	12	8.3
Antibiotics	10	80	Metals	29	58.6
Iodinated contrast media	8	62.5	Pesticides	117	0
Other pharmaceuticals	20	60			

Most of the chemicals detected in the Subiaco wastewater had screening RQs below 1 (for the complete SHRA data, see the complete final report). The exceptions were N-nitrosamines, complexing agents and disinfection by-products (DBPs). The screening RQ for five of the nine N-nitrosamines (NDBA, NDPA, NEMA, NPIP and NMOR) was above 1. All N-nitrosamines have the same mechanism of action and therefore it is possible to assume an additive model which indicates a risk for human health if the water was used for drinking purposes.

Numerous pharmaceuticals were detected in the secondary wastewater. However, health values are set in the µg/L concentrations, whereas the measured concentrations in the wastewater were in the ng/L levels. Therefore, screening RQs for all the pharmaceutical compounds were one to three orders of magnitude below 1.

Floreat Infiltration Galleries

Due to restrictions to the analytical methods at the time of this study, it was determined the concentrations of the majority of the chemicals detected in the wastewater (described above) were too low in the groundwater within the MAR scheme to be accurately studied. Despite this, five pharmaceuticals (carbamazepine, temazepam, oxazepam, diazepam, and phenytoin) were found to be easily detected in the groundwater within the MAR scheme and were therefore used as an example of the behaviour of trace organics in an aerobic aquifer used for MAR.

Screening RQs were calculated using the mean concentration RQ(mean) and the maximum concentration RQ(max) for the detected pharmaceuticals. Screening RQs were calculated using the Limit Of Reporting (LOR) for the undetected pharmaceuticals as a worst-case scenario. Health values were calculated assuming a proportion of intake from water of 90% instead of 100% to account for other potential sources of intake such as food. Calculated RQs were one to three orders of magnitude below 1 (Table 18), indicating very low health risk. Screening RQ(mean) values in the extraction bore for temazepam (RQ = 0.03), oxazepam (RQ = 0.008) and carbamazepine (RQ = 0.001) were lower compared with the screening RQs in the infiltration galleries indicating a decreased concentration of the pharmaceuticals in water recycled through the Floreat Infiltration Galleries.

Table 18. Risk Quotients of pharmaceuticals at the Floreat Infiltration Galleries

Pharmaceutical	LOR (µg/L)	LTD (µg/L)	Health Value (µg/L)	% detection	Detected in FIG (µg/L)		RQ mean	RQ max
					mean	max		
Temazepam	<0.1	10	5	86.6	0.21	0.31	0.04	0.06
Oxazepam	<0.1	30	13.5	87.9	0.24	0.34	0.02	0.03
Diazepam	<0.1	5	2	0	0.1		0.05	
Phenytoin	<0.1	300	135	0	0.1		0.0007	
Carbamazepine	<0.05	200	90	85	0.27	0.46	0.003	0.005

LOR, limit of reporting; LTD, Lowest therapeutic dose. RQs for phenytoin and diazepam calculated assuming measured concentration = LOD.

5.5. Conclusions from the Health Risk Assessment

The major human health risk of recycled water for non-potable uses is related to pathogens and not to chemicals. This is highlighted in the Australian Guidelines for Water Recycling (Phase1) (NRMMC-EPHC, 2006) and also in the health risk assessment using recycled water for fire fighting purposes (WSAA, 2004). Chemical contaminants are of concern only where recycled water is used for drinking purposes. In effect there is no requirement for human chemical standards specific to non-potable uses.

The MAR project was conducted as a research site where the various systems were tested at loading rates which had considerable bearing on the results. Therefore, these findings in must be viewed accordingly and not taken as the basis for accepting or rejecting an MAR project. The important consideration in planning for MAR is the understanding of the proposed system, its design features and management. The capability of the aquifer system and its capacity to attenuate the recharge water will determine whether additional barriers may be necessary for the system. The outcome to be achieved is a system that is designed to be ‘fit-for-purpose’.

QMRA

The QMRA modelling used the reference pathogens *Campylobacter*, *Cryptosporidium* and rotavirus to estimate the risk to human health. The exposure assessment considered microbial hazards through ingestion of sprays, garden irrigation and accidental ingestion, and then provided a risk estimate after taking into account a number of probability distribution function assumptions associated with the initial pathogen counts, decay rates, infiltration time and residence time in the aquifer. The residence time was based on an average of 70 days prior to recovery and use for irrigation.

The QMRA results suggest that reclaimed water extracted from the Floreat Infiltration Galleries poses an unacceptable microbial risk to human health if it were to be used for open space irrigation without further treatment. For the risk to be acceptable, under this model, a residence time of ~150 days is required. This must be considered in light of the trial conditions where the recovery rate was five times that of the injection rate and at a distance of 50 m between the injection and extraction points.

These results should be viewed as output risk estimates for the particular system in question, and although the approach is transferable, the actual assessed risk will change with various system parameters. The information should be interpreted in light of other information such as system hydrogeology and site-specific water quality monitoring data. Importantly, this work highlights that the QMRA approach can be used as a predictive tool to assist in identifying key constraints and requirements for full-scale MAR schemes (e.g. setting a residence time, and thus abstraction rate and distance between recharge and extraction) which ensure adequate pathogen log removal.

SHRA

The Risk Quotient (RQ) with a drinking water guideline level was used as a screening assessment of risk by comparing the measured chemical concentration with health values. A screening RQ below 1 is considered of low significance to health. A screening RQ above 1 indicates a requirement for more data on occurrence and fate and the development of a full health risk assessment.

Treated wastewater from the Subiaco WWTP was tested for 355 chemicals. These included: metals, inorganic compounds, nutrients, natural anthropogenic organics (disinfection by-products, pesticides and endocrine disruptors), persistent organic pollutants and radio-nuclides. A total of 88 chemicals were detected from all the chemical groups, except for pesticides, which were not detected. All chemical groups had screening RQ(median) values below 1, apart from NDMA and complexing agents. Although pharmaceuticals were detected, the RQs were one to three orders of magnitude below 1 (e.g. 0.1–0.001).

Based on the various chemicals analysed, the use of Subiaco wastewater as source water for non-potable MAR schemes as proposed in this project does not present a health risk from trace chemical contaminants when the recycled water is intended for irrigation purposes. There are only a few parameters that would require further treatment if the treated wastewater were to be considered as a drinking water source.

Five pharmaceuticals were tested at the Floreat Infiltration Galleries site. A total of 691 measurements were taken from the various bores situated between the infiltration galleries and the recovery bore (BH17), at a distance of 50 m. Only carbamazepine, oxazepam and to a lesser extent temazepam were detected in the bores. The levels of these three pharmaceuticals detected showed a gradual attenuation as the water moved away from the infiltration galleries. This is most likely to be due to dilution and dispersion within the aquifer as laboratory column experiments indicated that there was no degradation of these chemicals in the aquifer below the infiltration galleries. The screening RQ(mean) values in the extraction bore were: temazepam (RQ = 0.03), oxazepam (RQ = 0.008) and carbamazepine (RQ = 0.001). These represent one to three orders of magnitude below 1, indicating very low health risk.

6. CONCLUSION

Through the research undertaken in four interlinked work packages, this project has successfully demonstrated the applicability of using MAR in urban areas of Western Australia for the recycling of water for non-potable uses. The overall outcomes have shown that MAR can be a viable mechanism to assist the recycling of water while having a minimal impact on the urban environment.

Work Package 1 established that infiltration galleries could be used to sustainably and efficiently recharge recycled water with minimal impact to the ground surface. The success of the infiltration galleries, however, depended on the materials used for construction, with the Atlantis Leach System® giving better results than coarse gravel. It was also shown that the ultimate success of a MAR scheme depends on the implementation of appropriate management and operation processes.

The field-based research was also able to demonstrate that microbial pathogens and nutrients such as organic carbon and phosphate were removed during the MAR process. It was determined, however, that due to the aerobic conditions in the superficial aquifer, nitrate persisted. Research in Work Package 2 using large laboratory columns demonstrated, that the nitrate could be effectively removed by promoting denitrification through the addition of extra carbon (as ethanol).

Pharmaceutical compounds from the diazapam group were also found to be persistent in the aquifer with no evidence of degradation. The concentrations detected in the aquifer, however, were orders of magnitude below the therapeutic dose and were determined not to be of any health concern for recycled water used for non-potable purposes in the chemical risk assessment undertaken in Work Package 4.

Other research undertaken within Work Package 2 showed that many of the trace organic chemicals that are usually considered a matter of concern by members of the community and regulators, (e.g. hormones such as estrogens and plasticisers such as Bisphenol A) are degraded in the aquifers. However, some of the other trace organic chemicals tested (e.g. the nitrosamines, carbamazepine and x-ray contrast media) can be much more persistent. The research also found that redox conditions and the composition of the aquifer matrix was important of the movement of the chemicals through the aquifer. This indicated that a careful and thorough assessment of aquifer characteristics is important for predicting the fate and behaviour of trace organics within aquifers.

No water recycling scheme, including any involving MAR, is going to be successful in the long term unless there is community support. The research undertaken in Work Package 3 focusing on community attitudes to MAR indicated that trust, emotion and subjective norm are all important drivers in how a water recycling scheme is received by the general community. A notable exception to this list was knowledge, which was found to have little influence on community attitudes. Thus, the notion that ‘education of the public’ is all that is needed for a water recycling scheme to succeed is false. The social research also demonstrated that community decision making frameworks in relation to MAR are complex and heterogeneous. This indicates that a ‘one-size-fits-all’ solution is unlikely for all MAR schemes and that community involvement from the commencement of any scheme is vital to gain acceptance.

Work Package 4, the final section of research in the project, involved determination of the health risk from microbial pathogens and trace chemicals if accidental exposure to recovered water occurred. The chemical screening health risk assessment showed that the concentration of trace organics in the recycled water was too low to be of any human health risk when the water is to be used for non-potable purposes.

The only calculable risks were found to be from microbial pathogens. The Quantitative Microbial Risk Assessment (QMRA) showed that for three exposure scenarios involving non-potable uses, the recycled water recovered from the Floreat Infiltration Galleries (as operated under the research conditions used) did not meet acceptable health risk levels for rotavirus and *Cryptosporidium* as set out by the Australian Guidelines for Water Recycling. Further analysis of the QMRA showed that these risks could be reduced to an acceptable level by either increasing the residence time in the aquifer or by adding an additional post-recovery treatment process (for example UV disinfection).

Overall the project has demonstrated that MAR using a method such as infiltration galleries can be a very successful mechanism to assist in the recycling of water in an urban environment such as Perth. Other types of MAR may be more applicable in other regions where surface recharge may not be as suitable, however this would require a close examination of local aquifer conditions and the local requirements for recycled water.

The outcomes of the project have also demonstrated that it is important to undertake a detailed examination of the hydrogeological characteristics of the aquifer to be used for an MAR scheme; and to obtain comprehensive information on the quality of the water used for recharge and the potential persistence of biological and chemical contaminants in the aquifer. This information should then be used to assess the potential risks to community health, the environment and operational procedures faced by the MAR scheme. The outcomes of this assessment can then be used to properly design the MAR scheme to ensure that these risks can be properly managed. The outcomes of the research in this project have shown that detailed planning and preliminary investigations, along with input from the community at the conception of any MAR scheme will result in appropriate design and management of the scheme that should ensure its long-term sustainability.

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