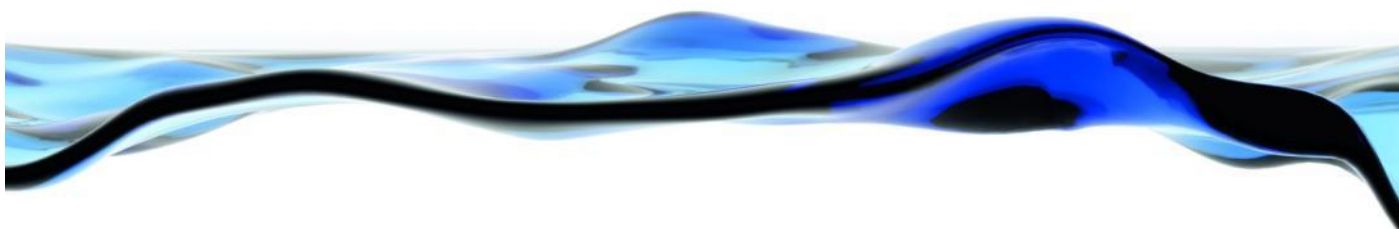# Managed Aquifer Recharge and Urban Stormwater Use Options:
Summary of Research Findings

Dillon P., Page, D., Dandy, G., Leonard, R., Tjandraatmadja, G., Vanderzalm, J., Rouse, K., Barry, K., Gonzalez, D. and Myers, B.

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MARSUO project partners:

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Foreword

The MARSUO project has been the first to lay down a serious and rigorous body of evidence in support of harvesting stormwater to augment urban water supplies. It has transparently examined the social, technical, economic and environmental facets and the immediate outcome is this report.

In Adelaide there is strong public support for stormwater for drinking and non-potable supplies and it has been in use by innovative local councils for 20 years, for public open space irrigation. Stormwater presents opportunities for securing city water supplies at much lower unit costs than desalination; indeed, had this project been completed six years ago, several states might have significantly reduced major capital outlays.

Owing to the mainly impervious nature of urban catchments, stormwater yields are more reliable and less drought-prone than rural runoff. The challenge of storage can be met by using surface reservoirs or aquifers, sometimes in combination. Urban stormwater quality is similar to that from open catchments that source drinking water for a number of Australian cities. The treatment and distribution technologies required are little different than those for conventional sources.

Despite the intuitive appeal of stormwater harvesting, the science and technology are not trivial, especially when aquifers are involved. This effectively places lower limits on project size to achieve economic sustainability. As is the case with any field of endeavour, a body of empirical practice rules has to be generated to ensure practical success. This project has made a good start in that direction.

The political realities of creating innovative systems have to be addressed too, as agencies and water businesses weigh up the threats and opportunities which are opened up, and the different relationships that have to be managed. Regulators need to create an environment which encourages innovation and fosters a market driven climate for all the players.

For many potential stormwater/MAR projects around Australia, there is insufficient value ascribed to environmental benefits, so more attention is needed in that respect.

Although the evidence from this project suggests that stormwater harvesting can be competitive in overall cost terms, every project is unique and a rational evaluation of costs and benefits is needed. This report represents a worthwhile contribution to the toolkit needed to guide decisions.

Chris Davis, Chair, MARSUO Steering Committee

June 2014

Managed Aquifer Recharge and Urban Stormwater Use Options: Summary of Research Findings

Executive Summary

Introduction and objectives

The Managed Aquifer Recharge and Stormwater Use Options (MARSUO) research project was a 3.5 year project that ran from November 2010 to May 2014. It evaluated in depth the quality of stormwater generated in the city of Salisbury, the treatment requirements and risk management measures necessary to assure safe water quality for public open space irrigation, third pipe reticulation to homes and for potential drinking water supplies. It also evaluated and compared the economics of these options for a case study at Parafield in Salisbury, South Australia, accounting for basic assessments of environmental and social impacts. Focus groups and two web surveys were conducted to evaluate public acceptance of the different potential uses of stormwater. An evaluation of biofilm in pipes of different materials was undertaken for mains water and stormwater to assess the likelihood of water quality changes and potential impacts on infrastructure maintenance. Studies of satellite sites in Australia and overseas were undertaken for comparative purposes, analysing stormwater quality and treatment requirements for drinking water use in relation to the Salisbury results.

These research studies were initiated in order to support the South Australian Government water security plan "Water For Good" that was announced in 2009. One of the key aims was for up to 60GL/yr of stormwater to be harvested in Adelaide, and up to 15 GL/yr in regional South Australia, by 2050. Additionally, these studies also became an integral input into the National Water Reform Initiative to assess the suitability of all forms of water for water supply, and to determine the economic benefits and public acceptance of diversification of urban water supplies. The overall premise was to identify and increase the range of efficient water supply sources whilst also reducing the environmental impacts of stormwater as Australian cities grow and urban areas consolidate. All of the approaches and principles that were applied were compliant with the Australian Guidelines for Water Recycling in the National Water Quality Management Strategy. Water quality was monitored at a number of sites to inform a risk assessment which then led to the development of a risk management plan.

Risk Assessment

Due to very short travel times of potential contaminants within the catchment, and the critical need for confidence in the quality of water recovered for uses with higher levels of human exposure, there is no fail-safe catchment management practice that can substitute for treatment of the water prior to use. It was found that exposure controls alone were adequate for managing risk for public open space irrigation and similar low exposure industrial applications. However, it was identified that appropriate treatments were needed to address health and aesthetic quality for residential third-pipe non-potable supplies and for reticulation within drinking water mains where the exposure rates are higher. These treatment processes were similar to those used for drinking water supplies when the raw water was sourced from open catchments.

Stormwater quality at satellite sites and treatment requirements for drinking water supplies

Parafield stormwater quality data were compared and found to be typical of other urban sites where stormwater is used, or has been assessed for use, as a source for drinking water supplies. Australian data was sourced from Orange (NSW), Mount Gambier (SA), and Fitzgibbon (QLD). International data was sourced from Singapore, Jinan (China), Haridwar (India) as well as the International Stormwater Best Management Practices (BMP) Database (2010). Despite the fact of significant climate and catchment variability represented by these locations, the evaluated stormwater quality data were surprisingly similar from a risk assessment perspective; in all cases requiring treatment for removal of pathogens, iron, turbidity and colour before being suitable as a drinking water supply.

Stormwater in distribution infrastructure

An evaluation of biofilm and sediment formation in pipes of different materials was undertaken for water derived from drinking water mains with low chlorine residual, and undisinfected aquifer-recovered stormwater. This was done in order to assess the likelihood of water quality changes and impacts on infrastructure maintenance if the drinking water infrastructure was to be used for non-potable (undisinfected stormwater) purposes. An increase in iron content in the undisinfected stormwater source water as well as increased biofilm growth in infrastructure were the two major impacts identified that will require control. Furthermore, analyses also suggest that the costs of pipe maintenance and risk management may be marginally higher in undisinfected stormwater systems due to the potential for increased biofilm growth. Water residence in aquifer storage was shown to be beneficial by reducing labile carbon concentrations (restricting biofilm growth), producing lower numbers of reference pathogen indicators (and potentially pathogens), reduced suspended solids concentrations and reduced dissolution of cement linings, than for water with limited aquifer contact.

Risk management

Risk-based management plans were developed for existing non-potable uses of Parafield-harvested stormwater, and for existing drinking water use of Blue Lake groundwater recharged by stormwater drainage wells in Mount Gambier. These are the first stormwater MAR risk-based management plans developed under the Australian Guidelines for Water Recycling, and serve as templates for other sites. The risk-based management plan for Mount Gambier stormwater recharge system was developed in consultation with the members of the Blue Lake Management Committee, to formalise recognition of current stormwater drainage practices and ensure continued protection of the water supply in relation to stormwater recharge. An audit of the Parafield stormwater harvesting system and managed aquifer recharge against the risk-based management plan was also undertaken and publicly reported. This is intended to serve as a model of best practice for auditing of stormwater harvesting and use against risk management plans. The audit found that City of Salisbury were managing the risks well on three scores designed to cover all risks. Recommendations for improvements that were distilled from the structured review were consolidated and prioritised to constructively contribute to the review and continual improvement of the system by its manager. A number of those recommendations deal with ways on engaging third parties who use the water to take up their responsibilities with exposure controls more diligently.

Economic assessment

An economic analysis was undertaken for twelve configurations for stormwater uses at Parafield, four each for public open space irrigation, residential non-potable third pipe supplies and drinking water supplies. Three cases included blending with recycled water to reduce the salinity of that water for irrigation use. Analyses took account of financial costs of each option in two ways, either including or excluding the costs of existing infrastructure in calculating levelised costs. In general the public open space irrigation and drinking water supplies had similar all inclusive levelised costs (from $1.31 and $1.47/KL respectively) and third pipe non-potable residential supplies were considerably more expensive (from $2.74/KL), and if retrofitting to existing subdivisions costs rose by a further $1.70/KL. These costs depend on estimated values and actual costs will vary from site to site.

That is, the cost of additional treatment and water management was less than the cost of constructing a new water distribution system for residential non-potable supply and keeping it isolated from existing water mains. A generic framework was developed that will assist authorities to define the scope for economic evaluation of stormwater use options including managed aquifer recharge projects. The analysis is in two parts; a cost-benefit analysis and a broader analysis including environmental costs and benefits, based on an ecosystem services framework. These are combined within a multi-criteria analysis.

Reliability of supplies

Modelling studies using 100 synthetically generated realisations representing 51 years of historical daily rainfall data were produced by the Goyder project on Climate Change. All events were routed through the catchment, harvesting system and aquifer using the daily hydrological model "WaterCress" to determine the reliability with which various annual demands would be met. It was found that after accounting for mixing with brackish water in the aquifer the demands assessed in the economics study could be met with 99.5% volumetric reliability of supply. Where this supply exceeds current local demand for public open space irrigation and industry the next lowest cost option for its use would be in drinking water supplies.

Public acceptance

Two stormwater options (third pipe residential non-potable and drinking water) were evaluated via focus groups and web surveys. Of more than 1200 participants a significant majority indicated that both proposed schemes were acceptable. However, participants were not willing to pay more for stormwater, particularly if it was of non-potable quality. Based on the information provided, participants also indicated a preference for stormwater over other alternative water options, namely desalination and purchasing more water from the River Murray, for future water supply augmentation of Adelaide's water supply.

There is a preference that government owned water utilities undertake such projects if treated stormwater is to be used for drinking water systems, due to the trust the community holds for water suppliers and regulators to provide safe water over the long term. Knowledge of more common stormwater terms appeared to contribute to acceptance of stormwater via managed aquifer recharge. This suggests familiarity with certain basic concepts may contribute to increased acceptance but a high degree of technical knowledge is not needed. If stormwater is intended to be harvested for drinking water use or for residential non-potable use for any project an appropriate public information and consultation process would be needed.

Implications of MARSUO project findings

From a national perspective the MARSUO project demonstrates the utility of stormwater for a wide range of future uses.

- It suggests that drinking water uses can be considered in addition to public open space and industrial use as well as third pipe residential supplies, in line with the NWI principle that all sources of water should be considered for future drinking water supplies
- Local data are needed, however an example shows that treatment costs to augment drinking water supplies with stormwater can be cheaper than the costs of establishing separate non-potable water distribution systems, and are similar to treatment costs to produce drinking water sourced from reservoirs in open catchments
- Aquifer storage (even in brackish aquifers) has value in increasing the capturable volume and through its potential for water treatment, and alone or in combination with reservoirs, reducing the unit costs of supply
- In a drying climate, the yields of urban catchments will diminish only marginally in comparison with decline in yields in rural catchments, and stormwater would provide a more dependable supplementary supply if systems were connected

- As drivers for sectors of the water industry can be quite different and the best commercial stormwater use options for any utility are not necessarily the optimal use for the city as a whole, and may therefore invoke loss of opportunity benefits unless such benefits are identified
- Policies are necessary to align commercial opportunities with best and most efficient use of the resource

Pathway to uptake of stormwater use options

Jurisdictions that have previously ruled out potential sources of water for cities without consideration of their merits should be encouraged to reconsider so as to fully implement the principles of the National Water Reform Agenda agreed to by the Council of Australian Governments.

Capitalising on the water supply opportunities for stormwater use options may require a more unified form of water governance than exists in most States, which recognises the integration of existing stormwater drainage and mains distribution infrastructure with different ownership and different established financial arrangements.

Water sensitive urban design, as encouraged in many jurisdictions, when implemented will improve the quality, increase the harvestable volume of stormwater and thereby advance opportunities for drinking water supplies. Urban designers should be free to consider the full palette of stormwater use options.

The MARSUO project shows that the technical and water quality/safety aspects are manageable using established processes under the National Water Quality Management Strategy, and the next step is to build processes that enable timely financial integration so that the highest valued projects are supported.

Conclusions from the case study indicate that appropriate institutional arrangements would need to be developed if they are not already in place to:

- Support identification and implementation of the most economic use of stormwater. This is particularly important where implementation requires integrated use of assets of more than one utility (e.g. stormwater drainage and harvesting infrastructure of a council water utility with reservoir, treatment and distribution infrastructure of a drinking water utility).
- Allow accounting for transfer of environmental externalities between institutions.
- Allow for the introduction of treated stormwater to the drinking water mains systems safely using local water treatment plants, in those jurisdictions where this is not currently permitted. Stormwater treatment plant operators should be subject to the same licensing requirements as current drinking water supply operators.
- Develop protocols for validation of aquifer treatment efficacy and aquifer specific operation guidelines to manage and control the variability in water quality.
- Provide options for residential non-potable third pipe supplies and third pipe supplies for public open space irrigation and industrial or other uses with treatment appropriate to the use (fit for purpose principle). Where appropriate and economic, allow for blending of recycled water with treated stormwater.
- Develop a system of entitlements to stormwater (in parallel with established rural water entitlements) to increase certainty for investments in stormwater harvesting
- Institutional reform (e.g. establishment of urban water banks) would also assist rational and transparent selection of the next sources of water, and combined with policies to require private sector investment to meet future water supplies of commercial subdivisions and developments, would accelerate uptake of the most economic water supply options that meet all criteria.
- Develop or strengthen urban land planning through land use planning zones that restrict locations of high hazard industries, provide green buffer corridors on urban water courses and ensure

retention of space for stormwater capture and treatment, and implementing water sensitive urban design throughout urban water supply catchments

- Continue to encourage good waste management practices and extend public information on environment and health protection as supportive measures for risk management for all uses of stormwater.

While the project has answered many questions, there are several areas where more work is justified. More information on environmental benefits would facilitate appropriate co-investment by governments in harvested stormwater supply options enabling more projects to be economic. Precursors, such as the Commonwealth's Clean Seas Program, enabled investment in wastewater treatment that enabled most of the pioneering projects on water recycling for agriculture. Similar program models for stormwater warrant consideration.

The project has revealed the potential for pathogen net attachment and inactivation in aquifers to alleviate some expensive and energy intensive disinfection treatments. However validation methods for pathogen removal in aquifers require research and development to allow reliance on aquifer treatment. Further evaluation and guidance on sustainable removal of biodegradable organic carbon, iron and turbidity in aquifers via ASR (recharge and recovery from same well) and ASTR (recharge and recovery from different wells) would also have merit for managing water quality in distribution systems.

1.   Project Objectives

In 2050 Australia's population is set to reach 35 million with 90 per cent of people located in cities. With this rapid urban growth comes an increased demand for water (that will be exacerbated by climate change) and the generation of more stormwater and sewage (wastewater). To keep providing high quality urban water services while maintaining water ecosystems and reducing our carbon footprint, we need a fundamental rethink of how we manage our urban water systems. This involves more integrated urban water management, harnessing water, wastewater and stormwater sources to maximise social, environmental and economic benefits. Australia's large cities have invested more than A$30 billion in new resilient water supplies, including desalination, decentralised supplies and various forms of recycling. Stormwater is a relatively untapped resource that could help us meet these future urban water supply demands. A project was conceived by a consortium of partners to assess this hypothesis and establish whether and how stormwater is a genuine option for Australian cities.

In 2011, CSIRO partnered with the National Water Commission and the Goyder Institute for Water Research in South Australia together with the City of Salisbury in Adelaide, Mount Lofty Ranges Natural Resources Management Board, SA Water Corporation, the former United Water International, University of Adelaide and University of South Australia to investigate using aquifers to harvest and treat stormwater for a range of urban water uses. The project, called 'Managed Aquifer Recharge for Stormwater Use Options' (MARSUO), investigated the public health and environmental risks, public acceptance and the economics of a number of different options for using stormwater via managed aquifer recharge in Australia. Managed Aquifer Recharge (MAR) is the process of deliberately adding water to aquifers for withdrawal at a later date.

A trial site was selected at Parafield in the City of Salisbury, approximately 17 km north of the central business district of Adelaide, South Australia. The site was chosen due to the presence of an existing stormwater harvesting facility together with two different forms of MAR and several types of existing uses for stormwater. These include public open space irrigation and industrial water supplies as well as blending with water recycled from treated wastewater effluent for reticulation in a residential area as third pipe non-potable supplies for toilet flushing and garden irrigation. Information from satellite sites in Australia and overseas also allowed water quality comparisons and risk assessments to be made and to ensure that the methods and principles were transferable.

The project initially focussed on stormwater quality evaluation to enable risk assessment for a range of potential uses including in drinking water supplies. This led to determining the treatment requirements and risk management measures for each form of use with differing levels of human exposure. In turn this allowed a financial analysis of each option for the Parafield site. In parallel with this were studies of public acceptance of stormwater for higher exposure uses, impact on pipe infrastructure of reticulation with stormwater to evaluate biofilm formation, impacts on asset life and potential changes in water quality in the distribution system. Modelling with historical and downscaled projected daily rainfall sequences was used to assess the reliability of stormwater supplies following harvesting and storage in an aquifer. Finally evaluations of urban stormwater quality were undertaken at a total of four areas in Australia and three in Asia where data permitted, to give perspective on the findings at Parafield. At one site, Mount Gambier, a risk management plan was developed for use of recovered water as a drinking water supply. The results of each component of work are presented in a series of Goyder Institute Technical Reports, and in peer reviewed journal papers derived from that work. This report was assembled to give a concise overview of the project in more detail than a four page brochure, and to make clear the linkages between project components.

2.   Water quality and risk asssessment

The City of Salisbury, a local government authority in the northern suburbs of Adelaide, is acknowledged as a leader in stormwater harvesting using wetlands and aquifer storage and recovery (ASR). Recovered water

from their ASR system is fed into a ring main and used for public open space irrigation, industrial water supplies and to dilute salinity of recycled water (treated wastewater effluent) in a residential non-potable supply throughout the suburb of Mawson Lakes.   The locations and land uses of the catchments for the Salisbury stormwater harvesting systems are shown in Figure 1.

The Parafield stormwater harvesting facility located at Parafield airport collects primarily from the Parafield stormwater catchment and is generally supplemented by pumping stormwater from the Cobbler Creek catchment. Rainfall at the Parafield Airport rain gauge has a mean annual rainfall of 438 mm (1972-2009). The Parafield catchment produces a mean annual runoff of approx 1300 ML/yr, excluding additional flows pumped from Cobbler Creek. The Parafield stormwater catchment has an area of 1,590 Ha and is primarily urban (73%). It is composed of mainly residential (36%) but also vacant land (13%) and industrial areas (8%). Roads and rail lines account for 19% of the catchment area. The industrial areas include a pharmaceuticals factory, a wool processing plant, a dairy processing facility and a beverage manufacturing factory and a variety of small to medium metal and cement manufacturing industries. A variety of commercial properties (5%) are also found, including a number of automotive service and repair businesses and numerous warehousing facilities. There are also a number of small market garden horticultural properties and a livestock grazing paddock adjacent the harvesting point. The eastern-most catchment on Figure 1 is an open catchment in the lower Mount Lofty Ranges that supplies the Little Para Reservoir and water treatment plant that feed into Adelaide's drinking water mains. The reservoir is less than 12 km by road from the Parafield harvesting facility, and is 35m higher in elevation.

Each catchment in Figure 1 was assessed for potential sources of stormwater quality hazards. This risk assessment considered the key water quality hazards as defined by the Managed Aquifer Recharge (MAR) guidelines (NRMMC-EPHC–NHMRC, 2009a):

- Pathogens (viruses, protozoa and bacteria)

- Inorganic chemicals

- Salinity and sodicity

- Nutrients (nitrogen, phosphorus and organic carbon)

- Organic chemicals

- Turbidity and particulates

- Radionuclides

Endpoints considered were human health, the environment (including the storage aquifer and irrigated areas) and operational infrastructure (harvesting, distribution and irrigation systems). The most significant hazard expected and found was from pathogenic microorganisms. Human pathogens generally enter stormwater through sewer overflows and leaks. Within the Parafield and Cobbler Creek catchments from 2006 to 2010, the five-year average annual number of sewer overflows per 100 km of sewer main was 16.5 and 17.5 respectively (United Water) (Figure 2). This overflow rate may be compared with 7 to 9.8 for the whole Adelaide metropolitan area from 2003 to 2007 (NWC, 2008). Overflows in the range of 14.5 to 50 per 100 km of sewer main per year are considered moderate to high for Australian water utilities (NRMMC-EPHC-NHMRC, 2009a). Other pathogen sources are from land grazed by livestock (faecal contamination of water and soils).
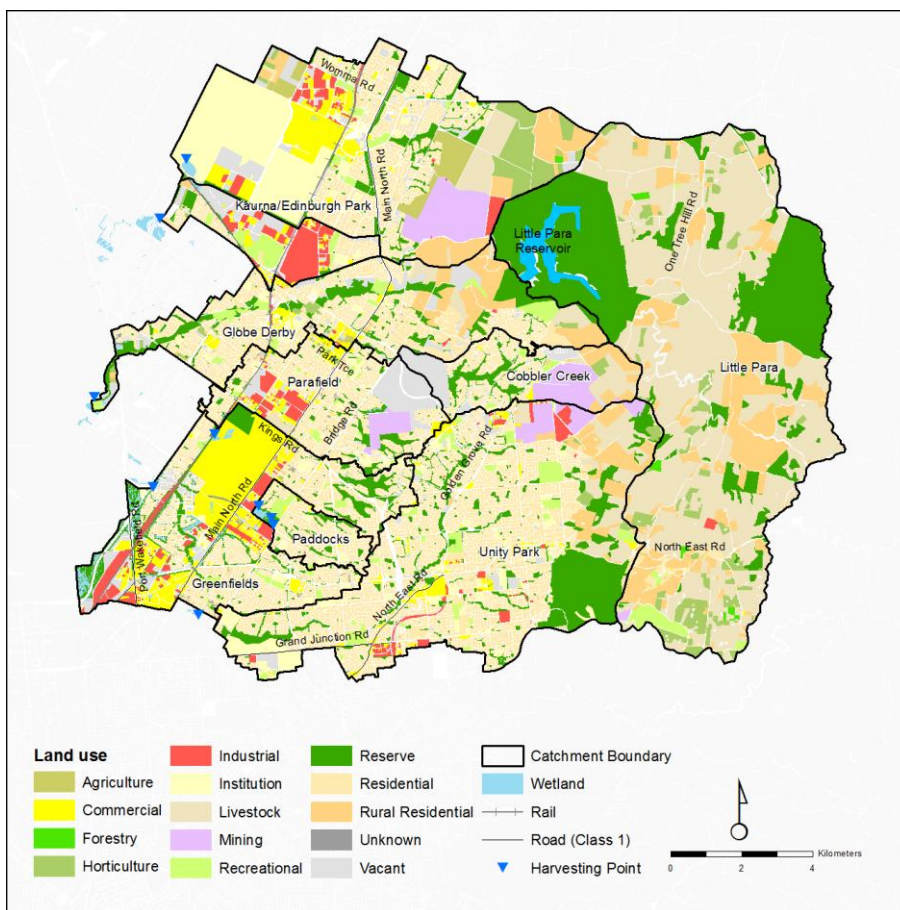
Figure 1 Catchment land uses related to stormwater harvesting and reuse schemes. Land use data sourced from DPLG (2011) and ABARES (2012) (from Page *et al.,* 2013a).
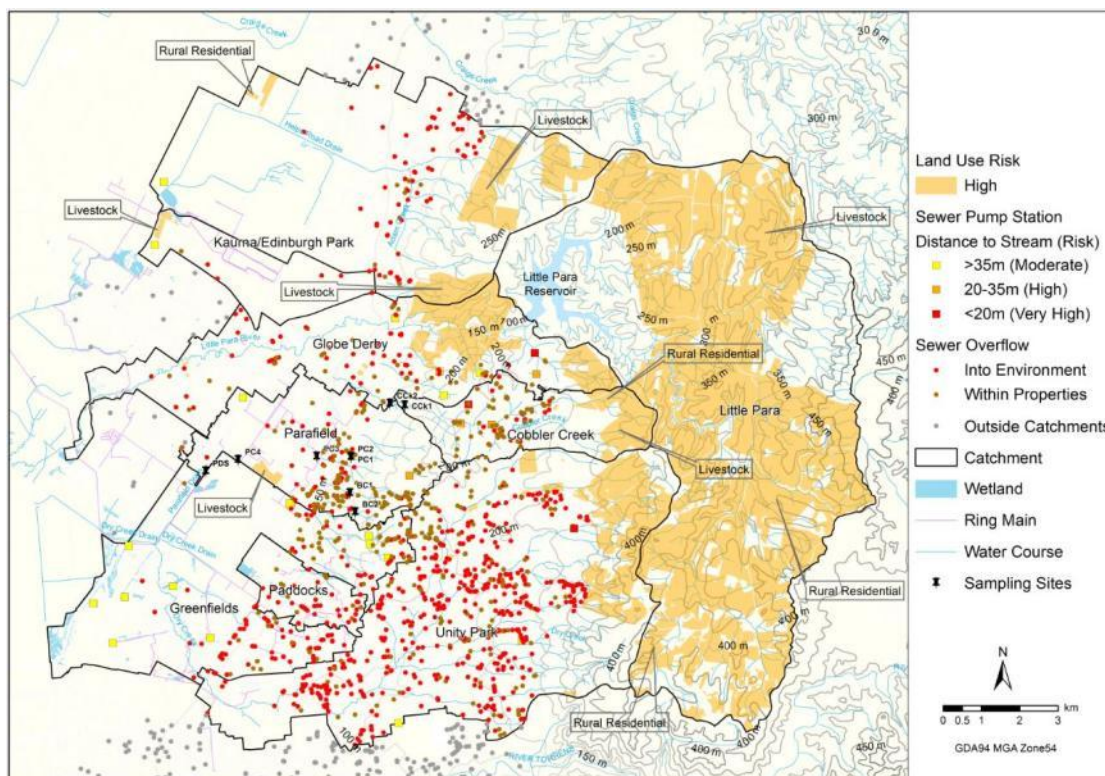
Figure 2 Catchment pathogen risks to public health relevant to augmentation of drinking water options. Sewer overflow data (2003-2010) sourced from United Water (from Page *et al.,* 2013a).

Managed Aquifer Recharge and Urban Stormwater Use Options: Summary of Research Findings

Targeted event-based composite sampling undertaken for pathogens in untreated stormwater was the most comprehensive of any found on urban stormwater in Australia or internationally. For the first time there was the data required by SA Health to evaluate the safety of stormwater harvesting for drinking water supplies. The 95th percentile number of reference microorganisms per litre are shown in Table 1, in comparison with default values for stormwater and wastewater taken from the National Water Quality Management Strategy Australian Guidelines for Water Recycling. The study reinforced the default values and showed marginally higher values for enteric viruses and marginally lower values for *Cryptosporidium* and *Campylobacter* (Page *et al.,* 2013a). These are in the order of 1000 times (3-log^{10}) lower than for 95th percentiles in wastewater, and similar to reservoirs of open catchments, e.g. 27 *Cryptosporidium* oocysts/10 L at Little Para Reservoir, South Australia (Page *et al.*, 2013a).

Table 1   95th percentiles for reference pathogens from this study and default values from Australian Guidelines for Water Recycling for stormwater and wastewater.

95th percentile (n/L)	Enteric viruses	*Cryptosporidium*	*Campylobacter*
Stormwater (this study)	**2**	**1.4**	**11**
Stormwater (NRMMC-EPHC-NHMRC, 2009a)	1	1.8	15
Wastewater (NRMMC-EPHC-NHMRC, 2008)	8000	2000	7000

Consequently, the log^{10} removals required for harvested stormwater were calculated for various uses with different levels of human exposure (Figure 3, adapted from Page *et al.,* 2013a). The data requirements and resulting values were determined and affirmed by the MARSUO Water Safety Expert Panel (see acknowledgements). For public open space irrigation, it was found that exposure controls alone are sufficient to meet health based targets (NRMMC-EPHC-AHMC, 2006). For third pipe systems, treatments such as chlorination and ultraviolet light (UV) (for *Cryptosporidium*) are necessary to meet the these targets. Ozone, membranes or other technologies are equally applicable. For drinking water quality, this would require aquifer treatment, if validated at 4-log^{10} removal, then disinfection with UV and chlorination. In the absence of validation of aquifer treatment, ultrafiltration or other technologies with similar pathogen removals would also be required.

Oxidation via disinfection can also be effective for removal of other water quality hazards such as iron. Salinity (EC) is managed by operational controls, nutrients (bioclogging) are managed by flushing irrigation equipment, turbidity is managed by wetland and aquifer treatment but may require additional treatment, while other hazards including radionuclides and organic chemicals do not need treatment to mitigate risk for these water quality hazards at their detected concentrations.

Monitoring of water at the wetland outlet revealed that most detected physical and chemical parameters met drinking water quality criteria, with the occasional exception of iron, turbidity, and colour. Water was injected into the aquifer via wells with recovery occuring from the same well (a process known as aquifer storage and recovery, ASR) or from separate wells (a process known as aquifer storage transfer and recovery, ASTR). Following recovery from the aquifer via ASR and ASTR wells the 95th percentile values for iron, turbidity and colour exceeded the drinking water guidelines. There was also one isolated unexplained detection of *Campylobacter* in recovered water after the standard initial purging of the recoevery well. Median iron levels also exceeded drinking water guidelines for ASR recovered water at Parafield, Kaurna Park, Paddocks and Unity Park stormwater harvesting schemes. In addition to the proposed disinfection (UV and chlorination) iron, turbidity and colour removal could be achieved either through media filtration or microfiltration to meet the drinking water guidelines. In the event of direct recovery to the mains distribution system, the treatment steps of microfiltration, pH adjustment and fluoridation would be required in addition to chlorination and UV.
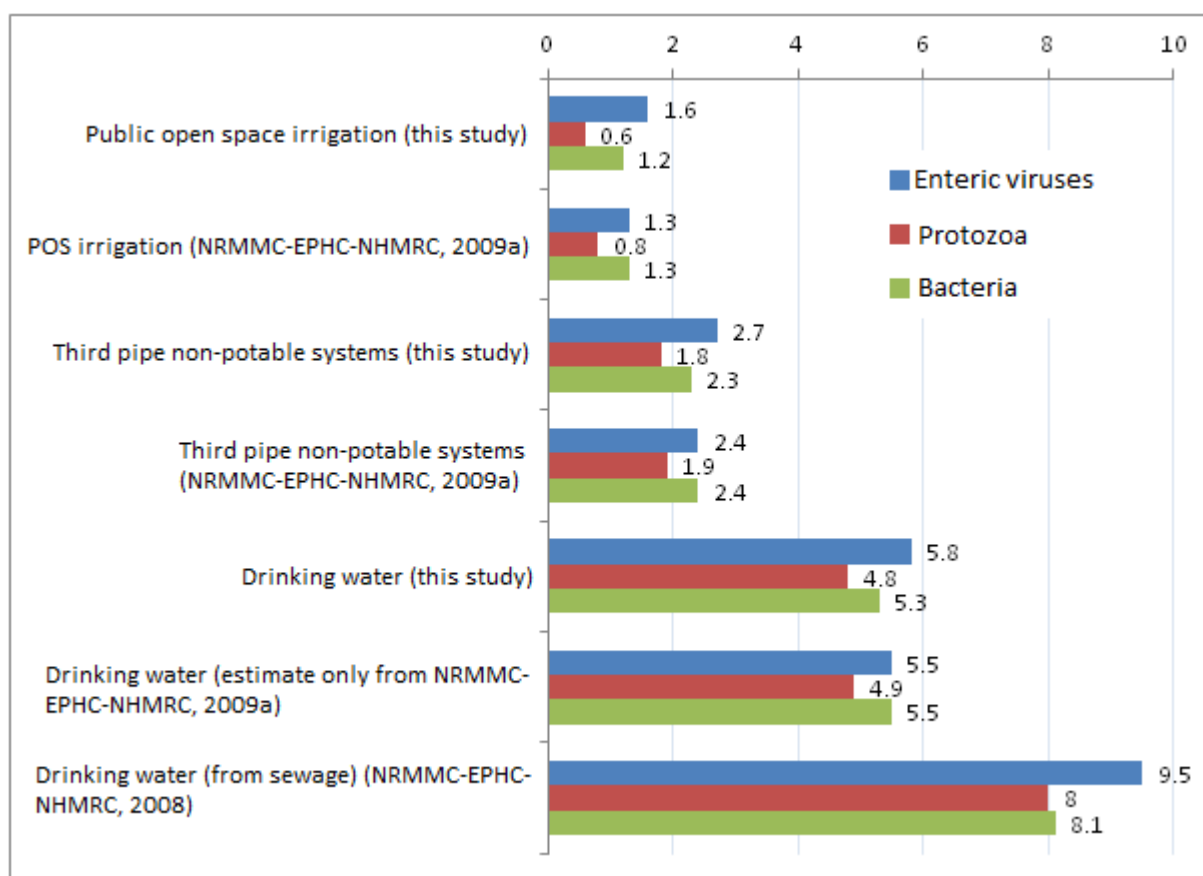
Figure 3 Log$_{10}$ removals required for safe use of stormwater for three types of uses based on pathogen data from this study and default values from Australian Guidelines for Water Recycling for stormwater and wastewater. (adapted from Page *et al.,* 2013a). (Each log removal reduces pathogen numbers by 90%)

An additional three years of intensive water quality monitoring has resulted in the same outcome as was reported by Page *et al.,* (2009) in an operational residual risk assessment for the Parafield aquifer storage transfer and recovery project. This information is reassuring for regulators and the community and is a consequence of pathogen levels being similar to those of the stormwater harvesting guidelines, and no material changes in values of other water quality hazards through the MARSUO project.

The travel time of water in the Parafield and Cobbler Creek catchments was less than an hour from the upper parts of the Parafield catchment to the harvesting point (Myers *et al.,* 2013). It is considered most unlikely with current technology that in the event of a spill or leak that all polluted water could be diverted from the harvesting point in time to produce an effective critical control point via diversion. Instead, water quality protection will rely on treatment prior to recharge and if necessary on recovery, depending on the use of the recovered water. This accords with the management of the Little Para Reservoir, where there is no opportunity to bypass a pollution event and reliance is on downstream treatment at the Little Para Water Treatment Plant. However in urban and rural catchments, the treatment barriers will be supported by taking account of stormwater quality impacts in land use planning and development approvals. Informing and encouraging communities on the need to protect stormwater quality will provide further support, but on its own does not provide a sure barrier.

3. Stormwater quality monitoring at satellite sites and treatment requirements for drinking water supplies

Stormwater quality was also assessed at sites interstate and overseas where data were available. These data were used to benchmark the findings of the research atParafield.

- City of Orange, NSW
- City of Mount Gambier, SA
- Fitzgibbon research site of the Urban Water Security Research Alliance, QLD
- City of Singapore, Singapore (following storage in a reservoir)
- City of Jinan, China
- City of Haridwar, India
- International Stormwater Best Management Practices (BMP) Database (2010) including data from various locations within the USA, New Zealand and Taiwan.

Considering the variety of climates and catchments included in the study, the evaluated stormwater quality data from all catchments, although variable, were surprisingly similar from a risk assessment perspective. Hazards with 95th percentile values (or numbers) exceeding the Australian drinking water guideline values at Parafield (iron, turbidity, colour and *E. coli*) also exceeded the guidelines at all other sites for which data were available. Similarly, hazards with 95th percentile concentrations below the Australian drinking water guidelines at Parafield (other metals e.g. zinc, salinity and nutrients including nitrate) were also below the guidelines at the other sites. The Parafield stormwater quality data were not atypical of stormwater quality for the parameters that could be assessed. Figures 4 and 5 are examples drawn from the Satellite Sites Report (Vanderzalm *et al.*, 2014b). In these box plots, upper (and lower) dots are 95th (and 5th) percentiles, end bars are 90th and 10th percentiles and boxes show 75th, 50th (median) and 25th percentiles, where detections allow.
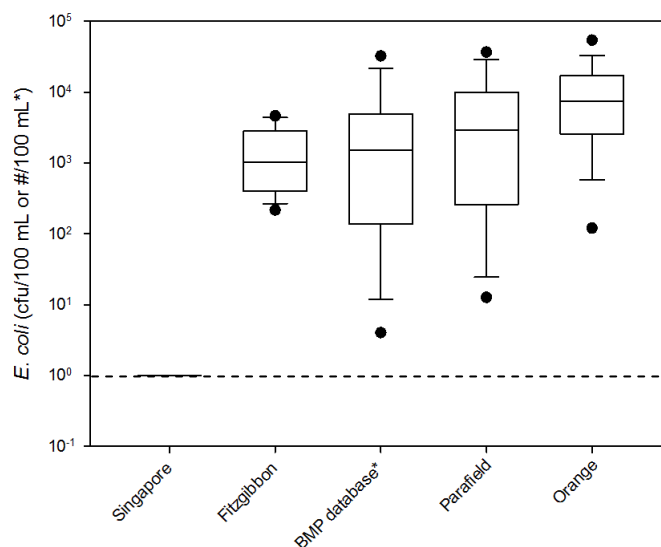
Figure 4   *E. coli* in stormwater from various catchments (Australian Drinking Water Guideline for *E. coli* is 0 cfu/100mL). Limit of detection is 1 cfu/100 mL (from Vanderzalm *et al.*, 2014b). Dashed line shows the limit of detection.
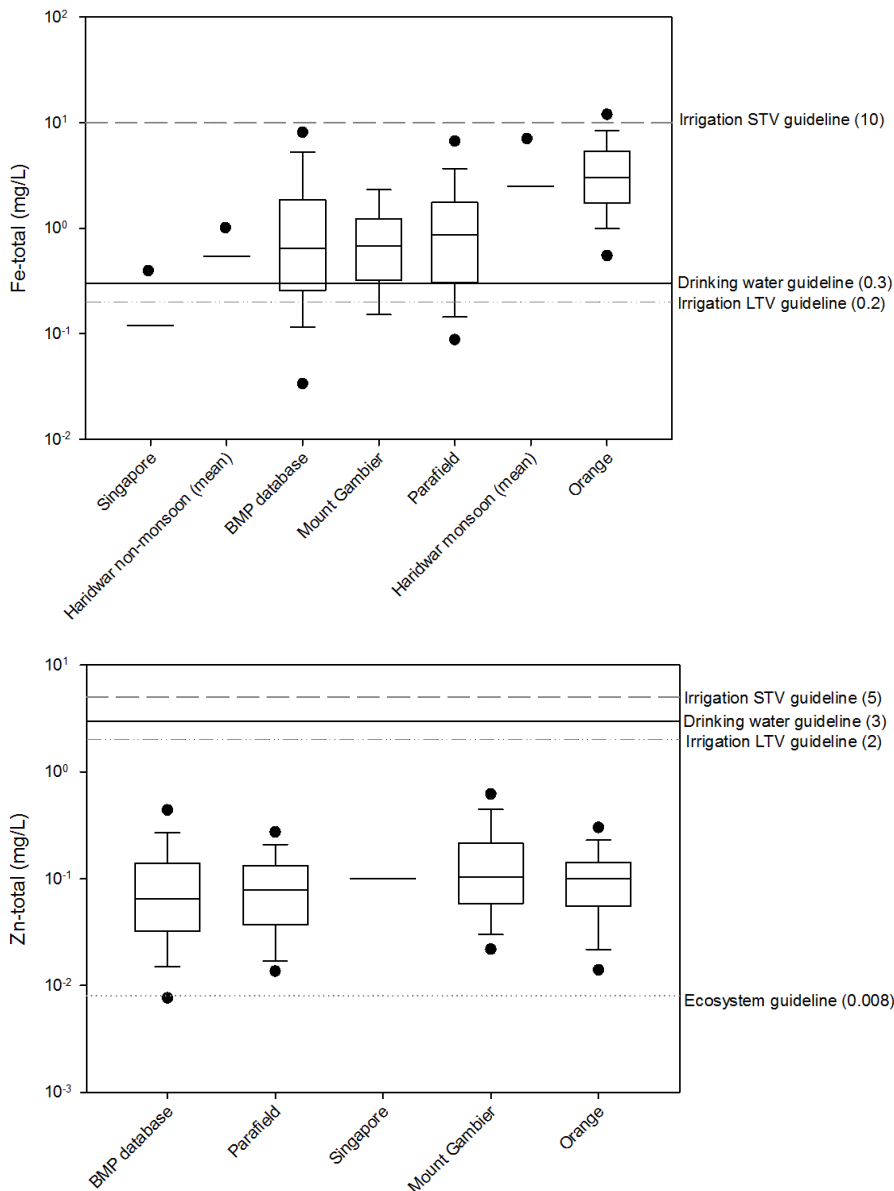
Figure 5 Total iron and total zinc (mg/l) in stormwater from various catchments (from Vanderzalm *et al.,* 2014b).

This implies that stormwater could potentially be regarded as a homogeneous water quality class with default values in the same way that the Australian Guidelines for Water Recycling regard treated wastewater effluent as a source water for all uses including drinking (NRMMC,EPHC, NHMRC 2008). The Parafield site is currently the only site with sufficient information on stormwater reference pathogen numbers to allow such an evaluation for pathogens, but the numbers accord with those derived for the Stormwater Harvesting and Reuse Guidelines (NRMMC, EPHC,NHMRC 2009a) as shown in Figure 3. If these stormwater quality default values were deemed to apply at a site, the minimum treatment to produce drinking water quality would include disinfection (such as UV and chlorination) and iron, turbidity and colour removal via either membrane or media filtration, including aquifer passage if removal through aquifer filtration is validated.

The Parafield assessment highlighted the very high resource cost of sampling intermittent, brief flows of stormwater for pathogen analyses to support maximal risk assessment for human health. At sampling points downstream in the treatment train, where water is continuously available for sampling and analysis of pathogen indicators, there was a decrease in median and range of microorganism numbers, and also in the proportion of samples with detections (Figure 6). This decrease in median and variability is the result of mixing, dispersion, and removal processes that occur within the wetland harvesting system and the aquifer.

It is suggested that Australian Guidelines for Water Recycling be modified to make allowance for flow intermittency and the practicality of sampling points for maximal risk assessment. For MAR systems it is proposed that sampling of injectant (i.e. discharge from the wetland) is recommended in lieu of sampling raw stormwater directly.
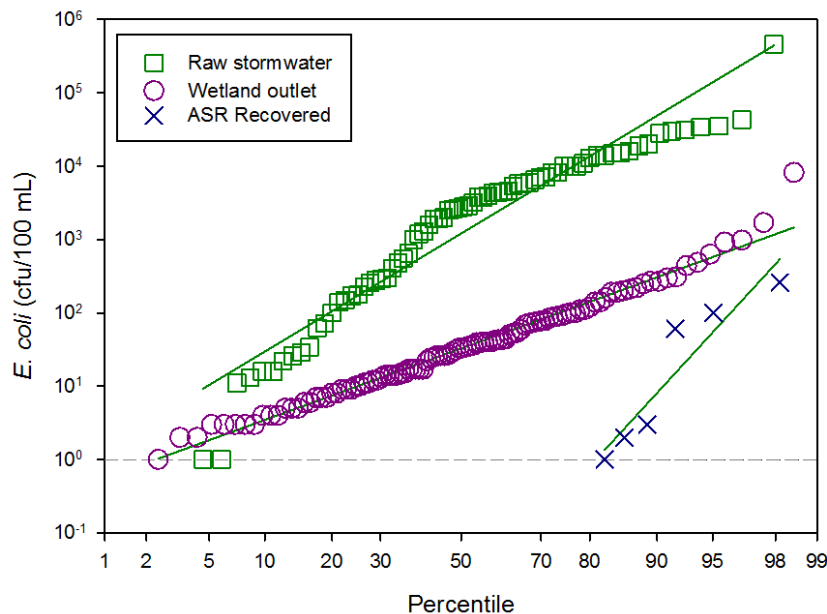
Figure 6 Lognormal cumulative probability plot for *E. coli* throughout the Parafield stormwater harvesting system Each point represents a sample with a detection of *E. coli*. (Limit of detection is 1 cfu/100mL, dashed line shows the limit of detection. *E.coli* were not detected in 82% samples of ASR recovered water. ASTR recovered water is not plotted as there were no detections (from Vanderzalm *et al.,* 2014b).

Aquifer treatment validation for pathogen removal was not addressed in this study but would require sampling of both the injectant and recovered stormwater. An approved validation methodology, such as a challenge test based on injection and recovery of virus and protozoan surrogates, remains to be developed. This is recommended as a high priority for future research.

4.   Stormwater in distributon infrastructure

Until this study of distribution systems that convey stormwater there was sparse information on water quality changes, growth of biofilms and corrosion of pipes conveying stormwater (Tjandraatmadja *et al.,* 2014). This information is needed to address risks to water users and to assess the likely maintenance requirements for stormwater distribution systems. Consultation with staff of United Water and SA Water led to selection of three pipe materials for evaluation; PVC, cement-lining and copper. An experimental rig was designed to simulate the normal operation of pipe systems with 16 hours of flow and 8 hours quiescent period each day for ten months. Two identical rigs were established (Figure 7) each containing 45 m pipe buried 0.6 m below ground including a 3.2 m length of pipe with removable 'coupons' of the three materials accessible from a covered pit, and a pump and header tank to allow recirculation and top up. The coupons could be analysed for biofilm biomass and composition and corrosion of materials.

One rig was sourced from stormwater that had been treated in a wetland and stored in a limestone aquifer for variable periods before recovery to the distribution system. The other rig was to serve as a reference supply and was sourced from drinking water mains. However in this area mains water experienced low flows and low or no chlorine residuals so this water was considered unrepresentative of drinking water and was referred to as 'baseline water'. Water quality monitoring in both rigs included continuous monitoring probes (temperature, pH, oxygen reduction potential and electrical conductivity) and sampling points for analysis of a broad range of analytes, including probe validation parameters, major ions, nutrients, metals, sediments, turbidity, colour and *E. coli*.

Figure 7 Photos of experimental rig: (a) Biorig pit and control room; (b) Biorig section showing coupon housing; (c) Rig header tank; (d) Secured (fenced and alarmed) pump shed and site; (e) Flow control instrumentation, (f) Manual boom gate to restrict site access.

Water quality in the stormwater rig had greater variability than the baseline water and 95th percentile concentrations for labile organic carbon, iron, suspended solids, turbidity and colour were higher than in the baseline rig. However, water corrosivity to cement was lower in stormwater. There were indications of slough off of biofilm from both rigs. Biofilms were found on coupons of all materials in both rigs, with variations over time from 10^5 to 10^7 total cells/cm^2 (derived through flow cytometry) and 10^1 to 10^6 viable cells/ cm^2 (derived through plate counts) with initially fewer cells on copper than other materials and no significant difference in biodensity between rigs. Bacterial and eukaryotric communities in bioflim samples

9

were determined through DNA analysis and pyrosequencing. Greater biodiversity was found in the stormwater rig biofilms and these contained a greater diversity of iron oxidisers and sulphate reducers, which can increase the potential for discolouration of water and for odour and corrosion of cement lined pipe under anaerobic conditions. Both rigs contained iron oxidisers, nitrifying bacteria and bacterial populations supported eukaryotes, including amoeba and nematodes. Eukaryote biodiversity was increased in baseline water samples over stormwater samples (Figure 8). Presence of potential pathogens within biofilm was found in both rigs, suggesting that a disinfectant residual would be required in both water types to reduce the risk of water supply contamination from dislodged biofilms.

Reducing biodegradable organic carbon, which may be achieved from longer residence times of water in the aquifer, is suggested as significant for reducing biofilm growth in pipes. It would also reduce production of trihalomethanes if stormwater is to be chlorinated as a primary preventive measure for biofilm growth in pipes. This would be essential for residential non-potable third pipe supplies where sufficient exposure control is not viable, and for drinking water supplies. With adequate exposure controls for public open space irrigation chlorination would not be required and operational experience suggests that biofilm slough off is not impacting irrigation system performance, but would be implemented if the same infrastructure is to be used for multiple purposes.
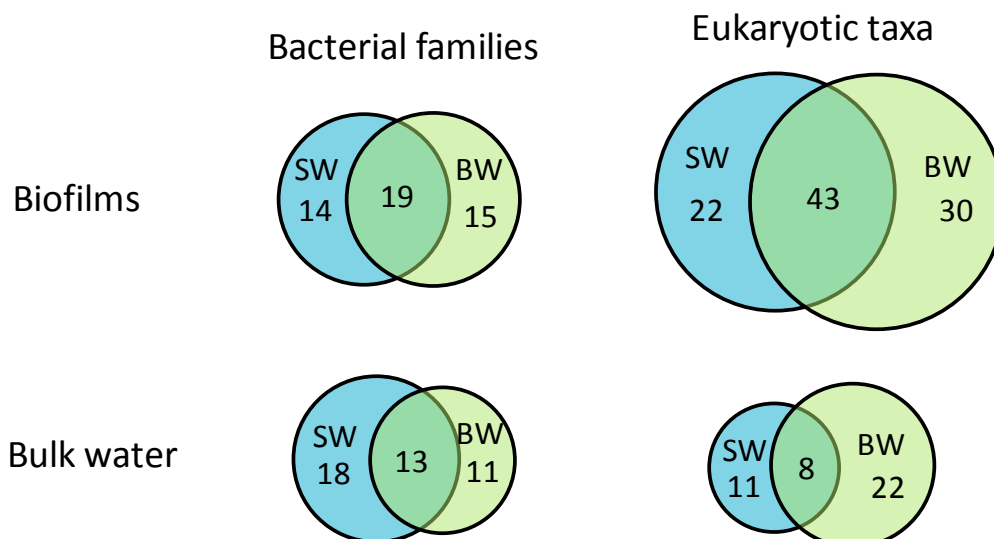
Figure 8 Unique and shared bacterial and eukaryotic taxa between the coupon biofilms exposed to stormwater (SW) and baseline water (BW) (from Tjandraatmadja *et al.,* 2014).

5. Risk management plans

5.1 Parafield stormwater harvesting system for non-potable uses

The Australian Guidelines for Water Recycling (NRMMC-EPHC-AHMC, 2006) require that a risk management plan be prepared to protect users of recycled waters. The project has developed a risk-based management plan for all of the current non-potable uses of water from the Parafield Stormwater Harvesting System (Page *et al.,* 2013b). These uses include stormwater supply to the Mawson Lakes Recycled Water Scheme for dual reticulation and unrestricted municipal irrigation, and stormwater supply for industrial uses and restricted municipal irrigation.
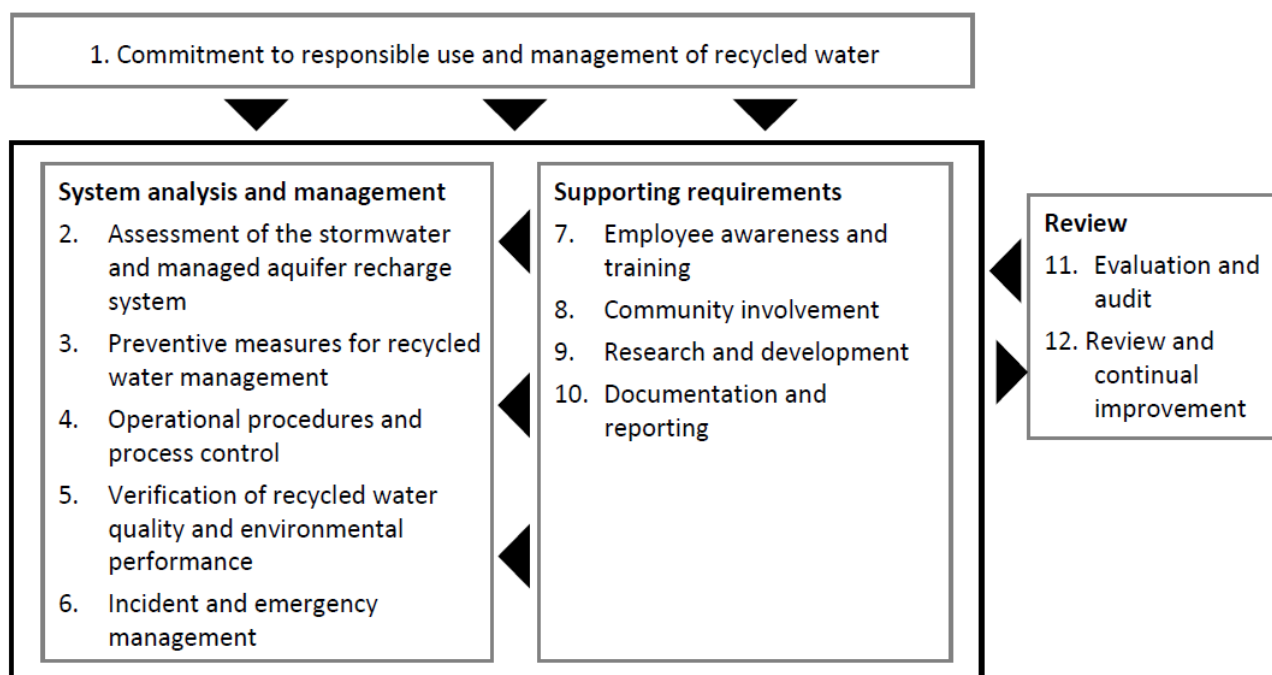
Figure 9 The elements of the framework for management of water quality and use (adapted from NRMMC-EPHC-AHMC, 2006; NRMMC-EPHC-NHMRC, 2009b) form the basis of the risk-based management plan (Page *et al.,* 2013b).

The Plan, prepared in consultation with City of Salisbury, SA Water and the MARSUO Water Safety Expert Panel, provides a basis for subsequent audit. It includes an activities schedule developed by the City of Salisbury that covers tasks to be undertaken monthly, quarterly and annually each linked to the element of the risk management framework that it addresses. This Plan fills a gap that developed as a result of the recycling system being established in advance of the Australian Guidelines for Water Recycling. The document, like other outputs from this project, is accessible from the Goyder Institute website. It is the first publically accessible stormwater harvesting and use risk management plan developed in Australia or elsewhere that covers the twelve elements of the risk management framework. Its publication in 2013 provides a national prototype for risk management plans for stormwater harvesting and use.

5.2 Audit of Parafield stormwater harvesting system for non-potable uses

As a final phase of the risk management aspects of the Parafield project within the MARSUO project, an independent audit was conducted by Daryl Stevens of Atura Pty Ltd on the Parafield stormwater harvesting system for non-potable uses. The audit was against the risk management plan and also critiqued the plan and was reported and published on the Goyder web site (Stevens, 2014). This is intended to serve as a model of best practice for auditing of stormwater harvesting and use against risk management plans. The audit found that City of Salisbury were managing the risks well on three scores designed to cover all risks,

with scores of 93%, 96% and 88%. Recommendations for improvements that were distilled from the structured review were consolidated and prioritised to constructively contribute to the review and continual improvement of the system by its manager. A number of those recommendations deal with ways on engaging third parties who use the water to take up their responsibilities with exposure controls more diligently.

5.3 Mount Gambier stormwater recharge and recovery for potable supplies

A risk management plan for recycling urban stormwater for drinking water supplies was also prepared (Vanderzalm *et al.,* 2014a). This was based on an a system of stormwater recharge that for 140 years has replenished an aquifer used as a drinking water supply in Mount Gambier (Figure 10) and a survey of the risks to stormwater quality of land uses and activities in the City of Mount Gambier (Figure 11). The 3,000 ML/year of stormwater recharge via drainage wells and sinkholes is similar to the volume pumped from Blue Lake each year and constitutes a significant source of water to Blue Lake. This risk management plan has been developed in consultation with the members of the Blue Lake Management Committee, to formalise recognition of current stormwater drainage practices and ensure continued protection of the water supply in relation to stormwater recharge. Implementation of the stormwater risk management plan by state and local government, the water utility and recharge bore owners will ensure the continuing high quality of Blue Lake as a drinking water source and as a tourist attraction.

SA government requirements for water quality recharged to the T2 aquifer of the Adelaide Plains even where it is initially brackish, are considerably higher than the requirements on those recharging the Gambier Limestone karstic aquifer containing fresh groundwater that replenishes a public drinking water supply. This project presents risk management plans that accord with the risks in each scenario, and if followed will assure protection of all environmental values of the recharged aquifers. The risk management plans developed through this project under the National Water Quality Management Strategy (NWQMS), if adopted, will resolve a historical discrepancy, that has added unnecessary expense in stormwater MAR in Adelaide, and given a comparatively lower degree of protection for Blue Lake.

However, it is important to note that the data so acquired over the last decade in Adelaide stormwater harvesting sites, if analysed, would allow verification of the effectiveness of current management and allow planned adjustment of monitoring requirements within future risk management plans. It is suggested that state governments review their ASR monitoring data at the time of licence renewals and revise data requirements to focus effort commensurate with risk for more efficient operations.
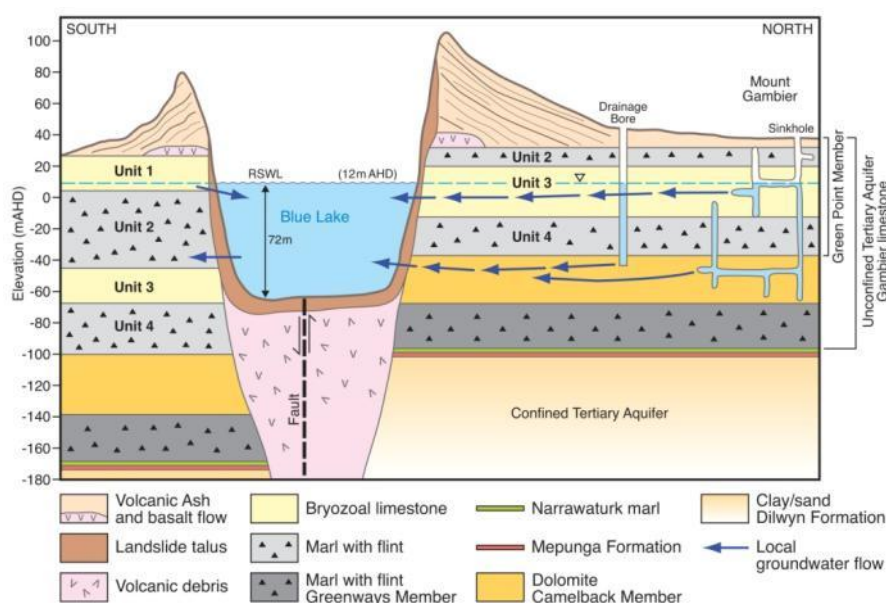
Figure 10 Conceptual diagram of stratigraphy in the vicinity of the Blue Lake (from Lawson, 2014).
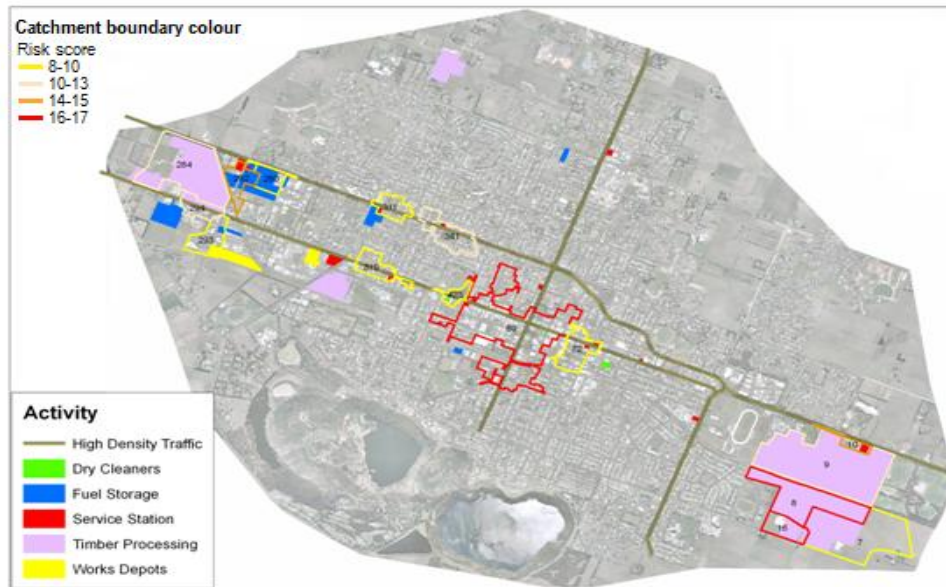
Figure 11 Stormwater catchments with highest potential risk to quality of stormwater runoff based on land uses and activities involving water quality hazards. Blue Lake is on southern boundary of map (from Vanderzalm *et al*., 2009).

Managed Aquifer Recharge and Urban Stormwater Use Options: Summary of Research Findings

6.   Net benefits of stormwater harvesting

6.1 Analysis of stormwater use options

Having identified, at Parafield, the quality of stormwater, the level of treatment required to safely use it for a range of final uses and the risk management activities required to ensure sustainable safe use, including managing the distribution system, it was possible to cost alternative projects to meet these uses. This was performed for three classes of use; public open space irrigation and industrial supplies, third pipe residential supplies of non-potable water and drinking water supplies. It was assumed, for simplicity, that water would be harvested from the existing stormwater harvesting system, at Parafield, and that water would be reticulated to these uses via existing infrastructure (Dandy *et al.,* 2014). Where such infrastructure did not exist it was costed using standard procedures. In the first phase net benefits analysis was undertaken dealing with monetised economic costs and benefits only. Firstly it was performed treating all existing infrastructure as a sunk cost. Subsequently it was analysed by costing all required stormwater harvesting and distribution infrastructure as new investment, so as to inform proponents of 'greenfield' developments in newly urbanising areas of the potential costs. The economic benefits of water having lower salinity than mains water are also considered within this analysis. In the second phase of the analysis, other environmental costs and benefits such as greenhouse gas emissions, impacts on coastal water quality and public green space and amenity were also addressed semi-quantitatively, using a multi-criteria planning framework.

For each class of end use four alternative system configurations were considered, each containing different components or preventive measures. In Figure 12 each line represents an option and dots indicate which components are present for each option. Eight of the 12 options involve managed aquifer recharge, three options involve blending stormwater with recycled wastewater, three options involve storing stormwater in Little Para Reservoir, ten options have a final treatment of the stormwater or blended water, and one option also involves intermediate stormwater treatment. For the third pipe options (5 to 8) a further distinction was made in the economic analysis between Greenfield developments (new subdivisions) and Brownfield developments (retrofitting an existing residential area). The analysis used 2012/13 costs and prices, a project life of 25 years and interest rate of 6%.
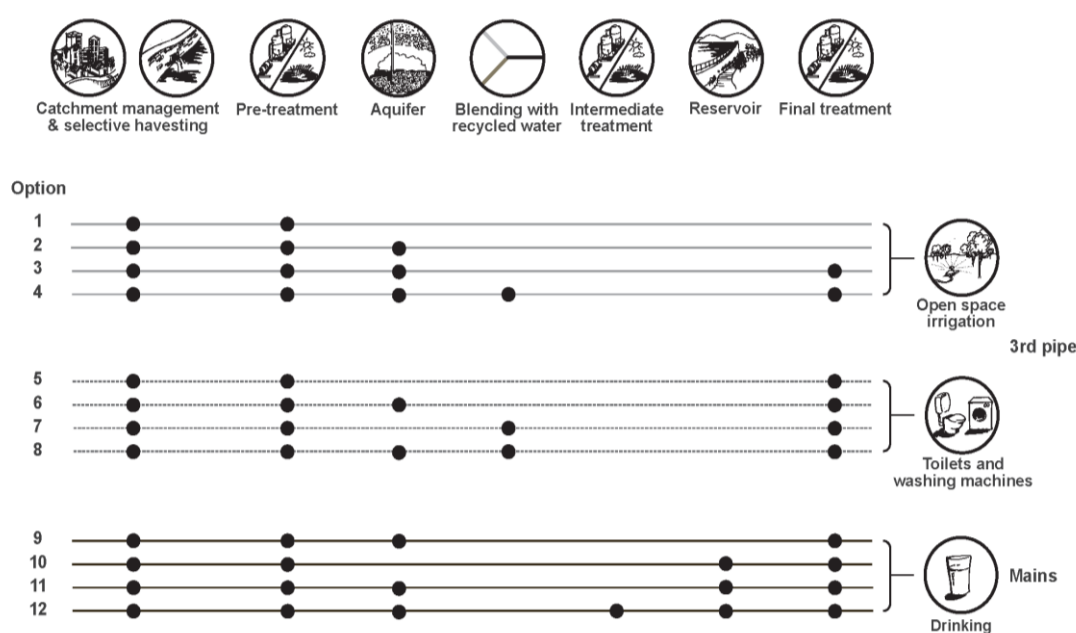
Figure 12 Twelve options for stormwater use at Parafield were evaluated.

Managed Aquifer Recharge and Urban Stormwater Use Options: Summary of Research Findings

It was also determined that the cost-benefit analysis should be undertaken from three different perspectives, namely state government, a local government water utility and a state-owned water corporation. Although the costs are the same, the benefits are quite different for the various entities. For example, SA Water (a water utility) can obtain water from other sources for $0.55/KL (operating cost only) so this caps the economic benefits to SA Water. However for City of Salisbury, the cost of alternative supplies is $3.45/KL (2012/13) for water purchased from SA Water. From a State Government perspective the Long Run Marginal Cost of water was calculated by SA Water in 2011 to be between $2.00 and $2.75/KL (ESCOSA 2012) which is regarded in economic terms as the value for state investment in expanding water supplies. These different benefit perspectives are shown as horizontal dashed lines in Figure 13. State benefits are further enhanced for stormwater harvesting through its contribution to State environmental objectives for urban areas and receiving waters. This means that projects with levelised costs;

- less than $0.55/KL, are economic for all parties,
- from $0.55/KL to between $2.00 and $2.75/KL are economic for State and local government,
- between $2.75 and $3.45/KL are economic only for local government, and
- exceeding $3.45/KL are uneconomic for all parties.

For the options considered at the study site involving 370 to 1100 ML/yr stormwater use, including costs of existing infrastructure, the least costs were found to be those for public open space irrigation, followed by drinking water supply augmentation. The most costly were third pipe residential supplies, especially for retrofitting existing residential areas. Public open space irrigation and industrial use had the lowest costs, from $1.31/KL (Option 4), involving blending with recycled wastewater from the Bolivar Sewage Treatment Plant and from $1.57/KL (Option 2), without blending. Drinking water supply augmentation costs ranged from $1.47/KL (Option 10 - pumping stormwater to the Little Para Reservoir (without aquifer) for storage, treatment and reticulation through mains) to $2.51/KL (Option 9 - supply to mains via a localised treatment plant with comprehensive risk management systems). Residential third pipe options started at $2.74/KL (Option 8G) where stormwater is blended with recycled wastewater from Bolivar STP. That is, the treatment costs for producing drinking water from stormwater are less than the costs of constructing a separate residential non-potable water distribution system. When costs of existing infrastructure were excluded from the analysis levelised costs were substantially lower, e.g. as low as $0.42/KL for public open space irrigation (Option 2). By comparison the levelised cost (including infrastructure) of the recently commissioned seawater desalination plant, if operated at full capacity, would be $2.41/KL. At 50 % and 20% capacity, this cost increases to $3.82/KL and $8.04/KL (respectively).

This levelised cost-benefit analysis reveals that if neglecting all environmental benefits and costs there are no options at full cost that warrant SA Water investment, between 5 and 7 are economic from a state perspective and 11 of the 16 options are economically viable for local government. Public open space irrigation with a blend of recycled wastewater and stormwater (Option 4) is the option with the lowest capital-inclusive levelised cost, due to the relatively lower costs of wastewater recycling than stormwater harvesting, which is required to dilute the salinity of recycled water for domestic irrigation use. In general public open space irrigation had the lowest costs followed by drinking water supplies, then third pipe residential use in greenfield situations and finally third pipe residential use in established suburbs.
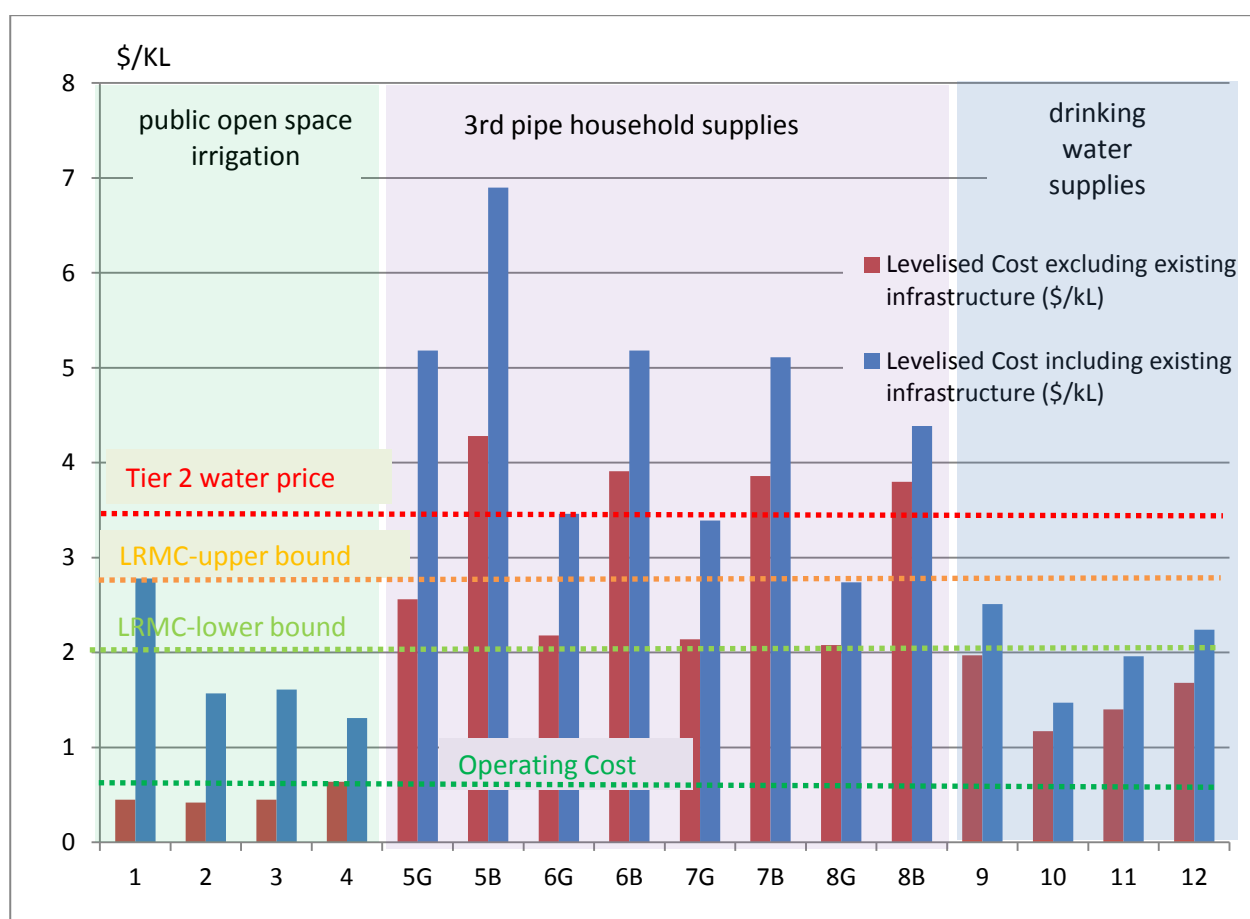
Figure 13 Comparison of the levelised cost of the various options, including and excluding the capital costs of existing infrastructure. Options 5 to 8 cover new suburbs (greenfield, G) as well as retrofit to existing suburbs (brownfield, B). Levelised costs are shown in relation to benefit per kL supplied from several perspectives. These benefits are shown as dotted horizontal lines. LRMC is Long Run Marginal Cost. This cost-benefit analysis does not account for the environmental benefits and costs of projects. (Figure is adapted from Dandy *et al.,* 2014).

Table 2 shows the net present values of the range of options in Figure 13. Present value (PV) is in standard use for evaluating economic viability of projects by considering the amount of money that if set aside and invested at a specified interest rate would exactly cover all the initial costs and stream of future costs (capital and operating) of a project when they occur. It can be used in the same way to account for the future stream of benefits of projects. This evaluation was performed in early 2013 for the options at Parafield. As with Figure 13, this considers the PV of new capital works and the future stream of operating costs, the PV of existing capital works, and the sum. For local decision making at this site, the existing costs would be excluded as sunk costs. However they are included here to be more representative of the total costs of establishing a stormwater harvesting system in an Australian city. The benefits are the savings on existing supplies, value of sales from additional third pipe supplies, and savings due to reduced salinity (or costs of increased salinity for cases where stormwater is blended with recycled water derived from treated wastewater). The PV of all benefits minus PV of all costs is the net present value, which is calculated from both a state and council prerspective and as a net present value per unit of water supplied. Note that Table 2 excludes environmental costs and benefits which are described later and should be taken into account.

Table 2 Net present value of Options 1 to 12 at Parafield including the cost of existing infrastructure from State perspective using a benefit of $2.75/KL (upper range of Long Run Marginal Cost) and of City of Salisbury perspective using a benefit of $3.45/KL) (from Dandy *et al.*, 2014).

Option	Annual supply (ML/year)	Present Value of Incremental Cost ($m)	Present Value of Existing Capital Works ($m)	PV of Savings in Supply Cost from Conventional Sources ($m)	PV of Benefits of Additional Water Supply ($m)	PV of Savings in Salinity Damage Costs ($m)	State perspective Benefit of $2.75/KL		Local government perspective Benefit of $3.45/KL	
							Net Present Value ($m)	Net Present Value per GL Supplied ($m/GL)	Net Present Value ($m)	Net Present Value per GL Supplied ($m/GL)
1	370	2.13	11	13.01	0	0	-0.12	-0.33	3.19	**8.62**
2	880	4.71	13	30.94	0	0	13.23	**15.03**	21.10	**23.98**
3	880	5.08	13	30.94	0	0	12.86	**14.61**	20.73	**23.56**
4	2100	17.06	18	73.82	0	0	38.76	**18.46**	57.56	**27.41**
5G	370	12.11	12	8.71*	4.68	0.12	-15.28	-41.28	-7.79	-21.06
5B	370	20.25	12	8.71*	4.68	0.12	-23.42	-63.28	-15.93	-43.06
6G	880	24.57	14	20.73*	11.13	0.05	-17.79	-20.22	0.24	**0.27**
6B	880	43.93	14	20.73*	11.13	0.05	-37.15	-42.22	-19.12	-21.73
7G	1000	27.30	16	23.55*	12.65	-3.72	-23.47	-23.47	0.80	**0.80**
7B	1000	49.30	16	23.55*	12.65	-3.72	-45.47	-45.47	-21.20	-21.20
8G	2100	55.54	18	49.46*	26.57	-7.82	-31.90	-15.19	19.08	**9.08**
8B	2100	101.43	18	49.46*	26.57	-7.82	-77.79	-37.04	-26.81	-12.77
9	880	22.19	6	30.94	0	1.04	3.79#	**4.30**#	10.62#	**12.07**#
10	1034	15.45	4	36.35	0	3.04	19.94#	**19.28**#	26.15#	**25.29**#
11	827	14.75	6	29.07	0	1.04	9.36#	**11.32**#	15.72#	**19.01**#
12	827	17.73	6	29.07	0	1.04	6.38#	**7.72**#	12.74#	**15.41**#

* Based on supply of 67% of non-potable demand from conventional sources due to the higher price of water to the consumer.

Without a policy change, this benefit is unlikely to be realised by state or local government as the water would be delivered to Little Para Dam or mains from which point the revenue benefit accrues directly to SA Water. Although SA Water is wholly owned by the State Government, SA Water regards its benefit of access to a new source of supply as being capped by the operating cost of alternative supplies. State intervention, such as introducing policies taking account of the full cost of supply, and requiring appropriate sharing of benefits by wholesale and retail suppliers where the state benefits, would be necessary to achieve the economic and environmental benefits through these options.

These costings for Parafield are based on an estmited annual harvested volume of 1100 ML/yr of which 80% is recovered from MAR operations yielding 880ML/yr, or without aquifer storage of 370 ML/yr. A further 6% loss through Little Para Reservoir evaporation and water treatment plant losses has been assumed. Subsequent research (reported in section 6.3) revealed that these estimates of annual supply had a volumetric supply reliability of >99.5%.

From a State perspective, the highest net present value of benefit of $39M is for public open space irrigation with harvested stormwater blended with recycled water from treated wastewater effluent. This is followed by $20M for drinking water via a new pipeline to Little Para Dam, noting that this net benefit would require new financial arrangements in order to materialise. The capital cost of a new pipeline and pumps to connect Parafield harvesting facility to Little Para Reservoir (in options 10 to 12) is only $5M of the $15.5M present value of incremental costs. Next best options are $12-13M for public open space irrigation for recycled stormwater alone and $4-9M for other drinking water options. No third pipe options

are economically viable from a State perspective. From a local government water utility perspective the same options occupy the first four rankings with the net present value of these four options being $58M, $26M (noting that this overstates the benefits as it allows no margin for the SA Water operator), $21M and $21M. Then, third pipe with blending to greenfields subdivisions (8G), becomes the 5th ranked option $19M, followed by the three remaining drinking water options at $16M to $10M. Other third pipe options are marginal (<$1M) to unviable.   If sunk costs were excluded this would increase net benefits.

Looking at the costs of schemes with and without managed aquifer recharge, MAR schemes can harvest more than twice as much water as schemes without either aquifer or reservoir storage and hence give lower levelised costs of water. This benefit would be further enhanced if treatment processes evident in the aquifer are validated and given credit within the treatment train for higher exposure uses.

6.2 Environmental costs and benefits

Environmental benefits of stormwater harvesting include:

- improved quality of coastal waters with consequences for seagrass health
- ecosystem health including commercial fisheries
- visual and aesthetic attributes of seawater for bathing
- tourism and coastal property values
- reduced costs of beach protection
- greening of the urban landscape with wetlands and parks that otherwise may not have been irrigated
- consequent health benefits from recreation and reduced urban heat-island effect
- reduced dependence on the River Murray
- lower consumption of electricity, if operation of the desalination plant or pumping from River Murray are reduced.

An ecosystem services framework for evaluation of benefits and costs was developed by Kandulu *et al.* (in press) for this project (Table 3) which is expected to be useful for future stormwater studies and to assist in identifying public benefit, and hence the case for government investment in stormwater harvesting (in addition to water supply benefits). While the net present value of reduced dependence on River Murray has been quantified at $1.7M/GL (Dandy *et al.,* 2014) in present value terms for substitution of stormwater for mains water supplies, the values of other benefits have not been reliably estimated. The largest environmental benefit of stormwater harvesting is potentially due to aesthetic coastal water quality improvements for Adelaide, if parallels with studies in Auckland are relevant. Studies to bridge this gap in knowledge would be important.   In the case of stormwater harvesting at Parafield, this value is likely to be small as water from this catchment discharges to Barker Inlet mangroves where there is minimal public access.

A multi-criteria analysis using the economic net present value, and benefit of reduced supply from River Murray and a minimal value for the benefit of reduced stormwater flow to the Gulf based only on the commercial fishery benefit yielded no change in the rankings of options relative to when only net present values were used. This possibly reflects the lack of quantification of environmental benefits, and should not be taken as representative of actual benefits at this site or elsewhere. Scores representing public support for stormwater harvesting, public trust of authorities for safety and willingness to pay current or higher water price, based on the first web survey (discussed in Section 7) , were normalised and incorporated in the multi-criteria analysis, and resulted in only marginal changes to the ranks of options. The public open space options were elevated above the previously second-ranked drinking water option, due to the assumed complete level of public support for public open space irrigation options (that already exist) over drinking options (that do not yet exist). For the various weights tested, the four highest ranked options were the same but in a slightly different order after the first ranked option (blended water for public open space irrigation), suggesting some resilience in the preference for these options.

Table 3 Impacts and related ecosystems services associated with the operation of stormwater harvesting at Parafield (Y is for impacts assessed quantitatively, y-qualitatively, and N - impacts not assessed during this stage of the analysis) (from Dandy et al., (2014)).

Ecosystem service type	Ecosystem Service value	Quantified (Y) / qualitative (y) / Not estimated (N)	Discussion
Cultural services	Conservation ethic	N	The magnitude of this "feel good" effect is unknown and it is unclear how to quantify
Provisioning Services	Fish production values and marine biodiversity	Y	Commercial fishing is not allowed in the Barker inlet, but it is a breeding ground for commercial fisheries. The effects of Nitrogen and Suspended Solids on seagrass die off were taken as a scalar on habitat that supports a wide range of marine life including fish.
	Freshwater provision	Y	This is covered directly in the cost-benefit analysis
	Recreation	N	Recreation values of detention areas are much more limited than other catchments, as the Parafield storage areas and wetland are fenced and netted and there is no public access.
Amenity	Coastal/ estuarine amenity – coastal water clarity	y	Improved water colour and clarity is a benefit for recreation, tourism and affects coastal property values
	Coastal/ estuarine amenity – beach restoration	Y	Loss of seagrass leads to mobilisation of sand, loss of beach protection in storms and loss of sand on recreational beaches. A sand pumping program is underway to replenish beaches, at a known cost that could be avoided by reducing nitrogen and susepended solids in coastal discharges thereby reducing seagrass loss and sand drift.
	Amenity space	Y	If water that otherwise wasn't available is used on open space, then the value of these areas may be capitalised in surrounding areas.
Regulation services	Flood mitigation	N	This was not estimated. The scale of ASR operation are unlikely to significantly affect volumes of stormwater runoff during peak flood events
	Erosion control	N	Degree of erosion and channel scouring (which may have ecological impacts) are unknown
	Climate/ air quality regulation	Y	Total green house gas emissions are estimated from construction through to operating phases
Supporting Services	Species in estuarine and coastal area	N	Maintenance of habitat which supports marine biodiversity is likely to be the best ecological indicator on which to focus

6.3 Reliability of supplies

Modelling studies using 100 synthetically generated realisations representing 51 years of historical daily rainfall data at Parafield airport were produced by the Goyder Institue for Water research Climate Change project. All events were routed through the catchment, harvesting system and aquifer using the calibrated daily hydrological model "WaterCress" to predict the reliability with which various annual demands would be met. A summer dominant demand pattern similar to current use was assumed. After accounting for mixing with brackish water in the aquifer using a freshwater storage depletion rate of 15.6%/yr calibrated on 10 years of operational records, the supply of 880ML/yr (12% mean annual catchment rainfall) assessed

in the economics study (Dandy *et al.,* 2014) is expected to be met with more than 99.5% volumetric reliability of supply at suitable quality (Clark *et al.*, in prep.).

Figure 14 illustrates the decline in reliability of supply with increasing annual water demand (from Clark *et al.*, in prep.). It also shows the sensitivity of the relationship between volumetric reliability of supply and the magnitude of the annual demand (expressed as a percentage of mean annual catchment rainfall), with respect to recoverable freshwater storage depletion rate in the aquifer. The curve showing 15.6%/yr freshwater storage depreciation rate represents the situation at Parafield where the salinity of native groundwater is 2020mg/L (TDS). The curve with no aquifer depletion represents the identical case in a hypothetical fresh aquifer operated so that cumulative recovery never exceeds cumulative recharge. The difference in annual demand met between these cases is ~10% (at any given reliability). Aquifers with intermediate freshwater storage depletion rates have intermediate yield-reliability relationships. In the case where recovered water needs to have lower salinity, such as with drinking water supplies, a minimum buffer of 200ML stormwater was superimposed on the higher storage depletion loss rate resulting in further 4% loss of annual demand met.
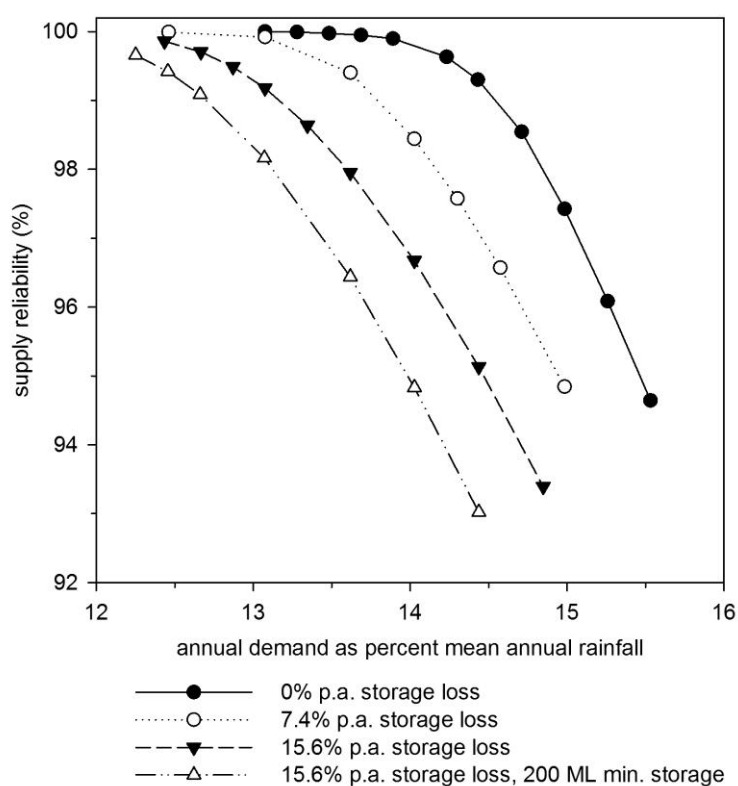
Figure 14 Plot of mean volumetric reliability of supply with respect to annual demand expressed as a percentage of the volume of mean annual rainfall on the catchment (from Clark *et al.*, in prep.). This figure shows the sensitivity of the yield-reliability relationship to freshwater storage depreciation rate. The curves showing 15.6%/yr freshwater storage depreciation rate represents the situation at Parafield. Each data point represents the mean of 100 simulations each of 51 years using daily rainfall data.

The reliable supply shown in Figure 14 significantly exceeds current local water demand for public open space irrigation and industrial process water suggesting that the next most economic option for surplus supplies would be in meeting demand for drinking water or in creating strategic reserves of drinking water. The water systems can be integrated with a capital investment of about $5M for pipe and pumps (Dandy *et al.,* 2014).

Using Goyder-derived downscaled rainfall predictions for a drying climate, the yields of urban catchments were shown to diminish only marginally in comparison with predicted yield declines in Mount Lofty Ranges (rural) catchments and would provide a more dependable supplementary supply if systems were connected.

Table 4 is a generalisation of the outcomes of the net benefits analysis at Parafield. Demand relates to that in the area that can be met most economically by a distribution system. Local factors may result in different relative costs and demands in other locations.

Table 4 Relative costs and demands of different stormwater use options for the Parafield stormwater harvesting system.

Supply type	Levelised cost			Demand
	Treatment	Distribution	Total	
P.O.S. irrigation and industrial	low	low	low	low
3rd pipe household	moderate	high	high	low
Drinking	high	low	low-moderate	high

Managed Aquifer Recharge and Urban Stormwater Use Options: Summary of Research Findings

7.   Public acceptance of stormwater use options

The evaluation of public acceptance was undertaken through three coordinated activities; (a) two hour focus groups with a total of 36 attendees were conducted in March 2011, (b) a web survey of 1043 Adelaide residents in October 2011, and (c) a web survey of 1218 Adelaide residents in March 2013.

Community focus groups were used to identify the level of knowledge of stormwater and relevant issues, including teasing out the reasons for beliefs held and the principle psychosocial factors forming such beliefs. They also examine community views on MAR as part of a stormwater harvesting and treatment scheme. The first web survey was used to compare stormwater with other sources of water and to differentiate preferences among three options; for drinking water recycling via the dam, drinking water recycling direct to mains, and residential non-potable uses via third pipe reticulation. The second, more detailed, survey was used to assess the impact of basic information on acceptance and to establish the stability of support between surveys for recycling of stormwater for drinking water and non-potable uses.

Focus groups revealed that eight key factors were related to acceptance. The first four are listed here in order starting from the most frequently referenced, *equality*. Putting stormwater into mains supply was perceived as increasing fairness and equality of water benefits, beyond just those people who have access to a third pipe supply. *Trust* was the second most cited factor and underpins community confidence in accepting stormwater and MAR. Reputation of the water utility was stated to be important to both trust and acceptance. *Environmental concerns* ranked third. It was recognised that harvesting stormwater helps to mitigate damaging environmental impacts in the sea, and use of wetlands and MAR was seen as 'environmental' and a 'natural' alternative. Fourth was *Cost to the householder* for the treatment and provision of stormwater. If stormwater was not drinkable, reference group participants considered that it should be cheaper than mains water supplies. The availability of factual information relevant to the MAR process and stormwater during the focus groups, via the presence of scientific experts, appeared to contribute to positive attitudes of acceptance. Other factors underlying public acceptance were found to include attitudes to waste, water security, water quality, information and effectiveness.

In the first web survey of October 2011, 1043 residents of the Adelaide greater metropolitan area were presented three alternatives for water supply each involving passage through a wetland before aquifer storage. Recovery involved non-potable supply to residences (Option 6), drinking water supplies via a reservoir treatment plant and water mains (Option 11) or drinking water supplies following treatment through a local water treatment plant and then into water mains (Option 9). Support for these options was 72% for the non-potable case and 57% and 55% for the drinking water options respectively. Five to seven percent did not support each option. The balance of respondents was uncertain and required more information to determine support.   Respondents did not differentiate between Options 9 and 11, suggesting that additional treatment barriers were not perceived as important, and there was considerable trust in the reliability of treatment processes. For Options 9 and 11, about 20% of respondents were inclined to protest whereas only 9% were inclined to protest Option 6. Respondents were willing to pay more for the drinking water options (around the current mains water price) than non-potable one (less than mains water price). Respondents also ranked stormwater above recycled wastewater, River Murray, groundwater and desalinated water in importance for future water resources.

In the second web survey in March 2013, 1218 Adelaide residents were randomly assigned to six survey groups with three groups receiving a survey about a drinking water use option (via aquifer and dam, Option 11) and three groups receiving a survey addressing a non-potable use option via aquifer and third pipe to residences (Option 6). Each group was given one of three information narratives; being either generic information, environmental information or safety information. Surprisingly it was found that opinions were unaffected by the nature of the supporting information, therefore, responses from these six groups could then be integrated into two groups, one for Option 6 and one for Option 11. Support for non-potable use was higher than for drinking water use and support for both was higher than in the 2011 survey. Acceptance varied with respect to descriptive and personal norms, perceptions of fairness, perceptions of trust, perceived effectiveness, attitudes towards stormwater, type of intended use, and knowledge. That

is, there are a number of more dominant factors that explain acceptance beyond that which can be explained by a simple drinking water/non-potable distinction. Psychological factors explained 81% of the reasoning behind people's acceptance of stormwater. Most respondents indicated that using stormwater through MAR was a good thing to do and believed it to be a beneficial, valuable, and wise endeavour (Mankad *et al.*, 2013).

Participants were asked to rate the importance of the different water source options, during non-drought and drought conditions, to supply Adelaide's overall water needs (Figure 15). Treated stormwater was the most preferred option for increasing Adelaide's future water supply (63%), compared with taking more River Murray water (23%) and desalination (14%) (Table 5). Interestingly, although the drought had broken, the margin in favour of stormwater over desalination increased for the drinking water use option and the order of preference for these options was unchanged from the 2011 survey results.
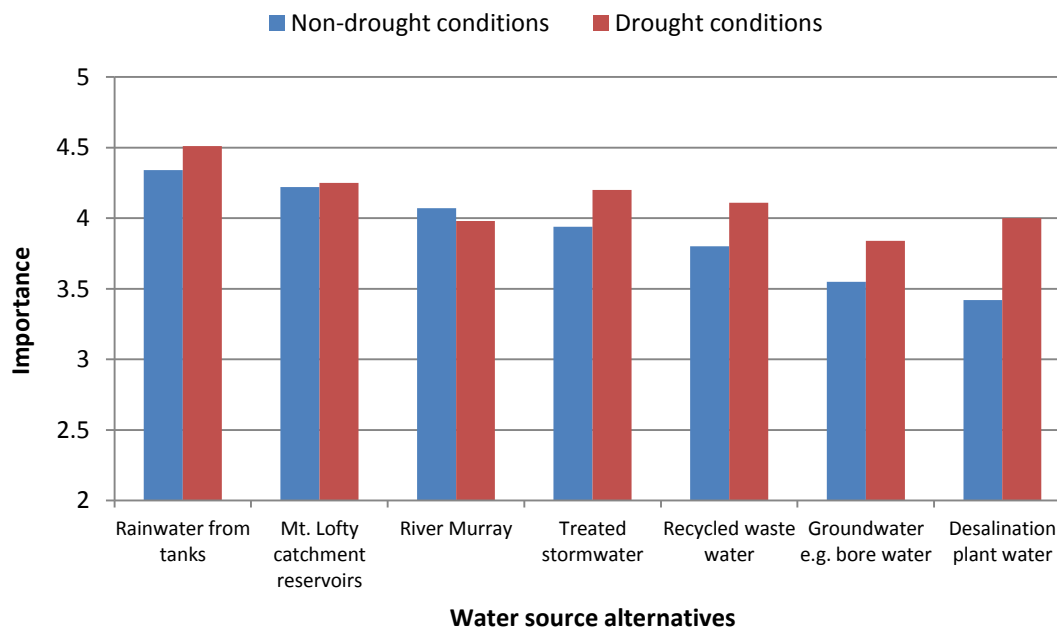

Figure 15 Perceptions of importance for alternative water sources during non-drought and drought conditions (from Mankad *et al.*, 2013).

Table 5 Most preferred option for increasing Adelaide's future water supply (from Mankad *et al.*, 2013).

Treated stormwater use	Taking more River Murray water	Desalination	Treated Stormwater
Non-potable use	22.2%	17.7%	60.1%
Drinking water use	23.1%	10.7%	66.1%
Total	22.7%	14.2%	63.1%

Note: Non-potable use n = 604, Drinking water use *n* = 614, Total *N* = 1218

Participants did not need a high level of detail when considering acceptance of stormwater. Communication activities about future stormwater initiatives could be framed to appeal to people's inherent attitudes and normative values associated with water. That is, it would be useful to highlight the stated acceptance of treated stormwater in the wider community, as well as endorsing stormwater with a message that might appeal to a person's sense of social value, such as environmental benefits for Adelaide

citizens. Participants thought that key communications activities could be presentation of simple facts disseminated via popular media outlets. Participants also favoured teaching school children about MAR of stormwater to familiarise the next generation and normalising stormwater as a usable urban water resource.
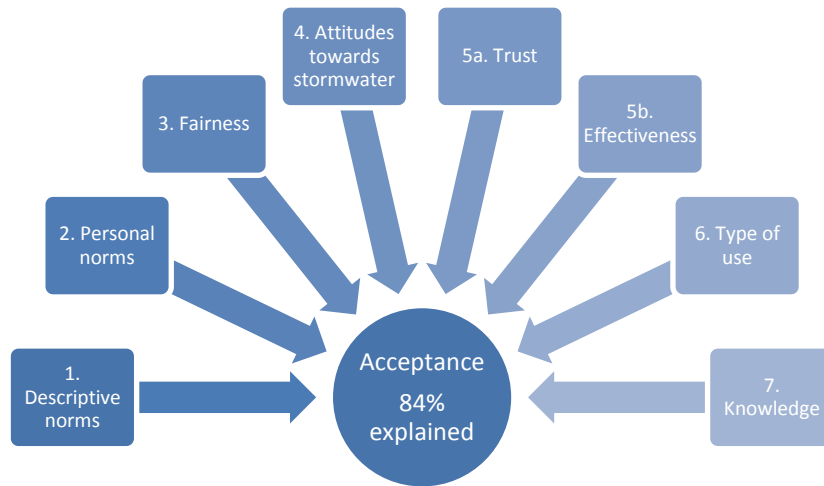

Figure 16 Illustration of factors contributing to acceptance of stormwater, ordered by relative importance (from Mankad *et al.*, 2013).

Policy related factors found to be important included fairness, trust and effectiveness. In the present study, unlike the focus groups, where attendees were informed that only new subdivisions would receive third pipe non-potable water, the absence of differentiation of beneficiaries was reflected in third pipe being perceived by respondents as fair and equitable. Policy implications of results suggest the need to develop stormwater use guidelines assisting building of trust in utilities, developing strategies for equitable household distribution of treated stormwater, and effectiveness in addressing water security, for example through entitlements to store with recovery in times of drought.

Managed Aquifer Recharge and Urban Stormwater Use Options: Summary of Research Findings

8.   Communications from project

The project has produced a series of published reports, peer reviewed journal papers and conference papers as well as conducting several workshops. These reports and papers are cited in the References.

Workshops conducted:

1. AWA Ozwater Workshop, Potable Water Reuse Via Aquifers: Managed Aquifer Recharge for Safe Low Cost Drinking Water Supplies: Adelaide, 9 May 2011, 40 attendees (AWA SIG Water Recycling/ IAH Commission on MAR / IWA SIG Water Reuse) (leaders Peter Dillon, Stuart Khan and Mark O'Donohue): Outcome - raising awareness of opportunities.

2. MARSUO Satellite Sites Workshop-Stormwater Risk Management: Adelaide, 12-13 May 2011, 25 attendees (leaders Declan Page and Peter Dillon): Outcome – willingness of partners to share information and data, and comparative paper presented at Singapore IWW and uptake of risk assessment approach by other local government bodies.

3. Pathogen Fate in Aquifers - a free national workshop for invited researchers and regulators. Adelaide 13-14 February 2012, 21 attendees (leaders Peter Dillon, Declan Page Saeed Torkzaban, Simon Toze, Jack Schijven (NL) and Liping Pang (NZ)). Outcome: - a research plan for pathogen fate research, resulting in NCGRT PhD student basing at CSIRO and a CSIRO strategic approp project formed in cooperation with AWQC.

4. Managed Aquifer Recharge with Stormwater – water quality issues – Beijing, 15 Oct 2013, - 40 attendees from 18 countries www.iah.org/recharge   (leaders Weiping Wang, Declan Page and Peter Dillon): Outcome - raised awareness on risk assessment approaches among groundwater fraternity.

5. Managed Aquifer Recharge with Stormwater - an NCGRT national workshop - Adelaide, 12-14 May 2014,   34 attendees, 3 countries (included 17 presenters and field trips) www.groundwater.com.au/events/50 (leaders Peter Dillon, Declan Page and Bruce Naumann): Outcome - comprehensive knowledge transfer to consultants, local government, utilities and regulators on MAR with stormwater, and an appreciation of operational and economic aspects of several projects.

Papers on outcomes of MARSUO project have been given at several conferences ;

1. OzWater, Perth, May 2013 (2 papers)
2. AWA SA Branch Conference, Adelaide, June 2013
3. SIA National Symposium, Melbourne, July 2013
4. IAH Congress, Perth, Sept 2013
5. ISMAR8, Beijing Oct 2013
6. SA NRM Science Conference, Adelaide, March 2014
7. OzWater, Brisbane, April 2014,

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