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RESEARCH ARTICLE

Fifty Years of Water Sensitive Urban Design, Salisbury, South Australia

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HIGHLIGHTS

- Low Impact Development was able to be adopted over a 50 year period by the City of Salisbury as it expanded from 4160 to 137,000 people
- The management of stormwater and groundwater was integrated through use of wetlands and managed aquifer recharge.
- Federal, state and local government contributed with developers and local industry to establish the integrated system as a commercial business supplying recycled water for non-potable amenity and industrial use.
- It has been shown with little additional water treatment, water originally treated through wetlands and aquifer storage could be safely withdrawn for a range of uses including as a potable water source.

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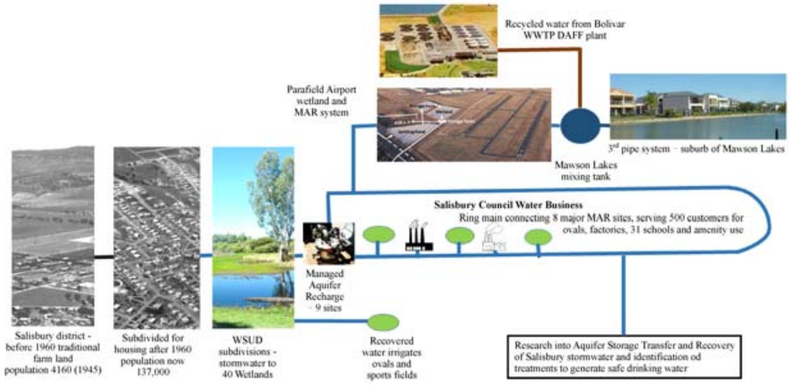
GRAPHIC ABSTRACT



ABSTRACT

Australia has developed extensive policies and guidelines for the management of its water. The City of Salisbury, located within metropolitan Adelaide, South Australia, developed rapidly through urbanisation from the 1970s. Water sensitive urban design principles were adopted to maximise the use of the increased run-off generated by urbanisation and ameliorate flood risk. Managed aquifer recharge was introduced for storing remediated low-salinity stormwater by aquifer storage and recovery (ASR) in a brackish aquifer for subsequent irrigation. This paper outlines how a municipal government has progressively adopted principles of Water Sensitive Urban Design during its development within a framework of evolving national water policies. Salisbury's success with stormwater harvesting led to the formation of a pioneering water business that includes linking projects from nine sites to provide a non-potable supply of 5×10^6 $m^3 \cdot year^{-1}$. These installations hosted a number of applied research projects addressing well configuration, water quality, reliability and economics and facilitated the evaluation of its system as a potential potable water source. The evaluation showed that while untreated stormwater contained contaminants, subsurface storage and end-use controls were sufficient to make recovered water safe for public open space irrigation, and with chlorination, acceptable for third pipe supplies. Drinking water quality could be achieved by adding microfiltration, disinfection with UV and chlorination. The costs that would need to be expended to achieve drinking water safety standards were found to be considerably less than the cost of establishing dual pipe distribution systems. The full cost of supply was determined to be AUD\$1.57 m^{-3} for non-potable water for public open space irrigation, much cheaper than mains water, AUD \$3.45 m^{-3} at that time. Producing and storing potable water was found to cost AUD\$1.96 to \$2.24 m^{-3}.

1 Introduction

Australia is a continent of 7.6×10^6 km^2 in area, and is one of great diversity of climate. Much of it is extremely arid. Only 12% of its rainfall runs off and is collected in rivers.

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Much of this is in the northern Australia tropical monsoon areas with sparse communities and little development.

Australia has a federal system of government. This comprises the Australian (sometimes called "Commonwealth" or "Federal") government, and the governments of the six states and two territories which make up the Commonwealth of Australia. The States/Territories governments generally have colonial origins tracing back to establishment by the British parliament in the eighteenth and nineteenth centuries. The Australian constitution, proclaimed in 1901, defines the respective roles of the Australian and States/Territories governments. In section 100, management of water is defined constitutionally as a States/Territories matter [1]. Within the States/Territories, there is a third tier of government that of local government, undertaken by incorporated municipalities and district councils.

State governments own water utilities in most states. Local governments generally own utilities in regional New South Wales and Queensland. Sewage services and wastewater treatment serve virtually all urban areas. Local governments in all states oversee stormwater management and planning under state legislation. Stormwater systems are universally separate from wastewater systems.

Since the end of World War II, Australia has had a significant population increase due to a strong migration support program and development of low density housing estates generally based on detached houses or duplexes built by public authorities and private developers. Most occupiers own their own houses.

Australia commenced developing its National Water Quality Management Strategy over 30 years ago. The Strategy has resulted in the production of 24 guidelines [2] encompassing drinking water, fresh and marine water quality, groundwater protection, sewerage systems, management of specific effluents, and water recycling (managing health and environmental risks, including for augmentation of drinking water supplies with recycled water, the use of stormwater and managed aquifer recharge). The Australian managed aquifer recharge guidelines [3], approved in 2009, is understood to still be the only risk-based guidelines addressing that topic. All these Strategy guidelines are then able to be adopted into States/Territories legislation and regulations for enforcement by Environment Protection Authorities and Public Health Departments. This approach contrasts with that in the United States where the developmental environment for stormwater is managed by the states with great variability. To address this problem, the Urban Water Resources Research Council (UWRRC) of the Environmental and Water Resources Institute (EWRI) of the American Society of Civil Engineers (ASCE) provides a forum to promote, advance and standardize Low Impact Development technology [4].

In Australia, a uniform basis for the management of water resources was brought together in the Intergovernmental Agreement on the National Water Initiative [5]. The detailed clauses guide the management of water in urban development and provision of water for both urban and rural use. The agreement included (Clause 92ii) development of national guidelines for evaluating options for water sensitive urban developments, both in new urban sub-divisions and high rise buildings by 2006. Consequently, a national guide for evaluating options for water sensitive urban design has been produced. This incorporates the integrated design of the urban water cycle, water supply, wastewater, stormwater and groundwater management, urban land use design and environmental protection [6].

The objective of this paper is to outline how a municipal government has progressively adopted principles of Water Sensitive Urban Design during a period of rapid urbanisation within a framework of evolving national water policies. It developed a water business for non-potable supply and has facilitated the evaluation of its system as a potential potable water source.

2 Development of a long-term stormwater system configuration

Until after World War II, the Salisbury Council was a local government authority for what was still a farming area north of Adelaide, the capital city of the state of South Australia. In 1947, Salisbury had a population of 4,160. Today it has a population of 137,000 as a part of the growing greater Adelaide population of 1.3 million [7]. Mean annual rainfall is approximately 430 mm with most falling in winter and very little in the hot summer months. Prior to European settlement, the several creeks that ran across the Northern Adelaide Plains rarely reached the sea, any remaining water flowing into marshlands behind sand dunes or mangroves [8]. The water otherwise infiltrated through streambeds to aquifers and via geological fault systems in the east margins of the plains to deeper underlying aquifers that are confined on the plains. The clay soils on the plains give slight diffuse recharge to generally thin shallow aquifers that are generally brackish except near streams, and low-lying parts of the plains were often waterlogged in winter. Future subdivision of the area for housing and industrial development was to markedly increase run-off and change the hydrology of the area, leading to the potential need for drains through the clay-rich soils to prevent flooding of low lying areas, ultimately addressed by use of distributed wetlands within a water sensitive urban design framework.

Although the South Australian Housing Trust, a government statutory authority, had undertaken some developments, Reid Murray Developments was the first private sector company to develop an integrated neighborhood development in Salisbury, incorporating houses, schools, shopping centers, and community facilities. Fifteen per cent of the area was reserved for recreational parks, with drainage lines retained as reserves. This led to the suburb of Para Hills, initiated in 1960 [9]. Stormwater from the development was collected in a retention basin to form a wetland and scenic lake, surrounded by extensive tree planting, trails and a popular dog park. The recreation center became known as "The Paddocks" after the former farm land. Subsequently, a program was initiated to conserve water from "The Paddocks" by Managed Aquifer Recharge (MAR) through use of Aquifer Storage and Recovery (ASR), which is the injection of water to an aquifer with recovery from the same well. The recovered stormwater was used to reduce the Council's demand for purchased drinking water used for irrigating the adjacent sports fields.

This developmental philosophy was followed for over 40 similar, though often smaller, aesthetic amenity wetlands built into land developments across the growing Salisbury Council area [10]. These now occupy over 200 ha of the total catchment area and have a mean annual harvesting capacity of 5.8×10^6 $m^3 \cdot year^{-1}$. The installation of ASR bores followed at many of these wetlands, the bores being licensed by the South Australian Environment Protection Authority with operating and monitoring conditions to ensure water quality standards could meet use criteria for the aquifer. Since water is vested in the state government, subsequent extraction approval for use of the stored water was managed by the South Australian government through what is now the Department of Environment, Water and Natural Resources.

The largest of the wetlands is the Greenfields wetland, constructed on an area of previously degraded agricultural land. Greenfields Wetlands came into existence in 1984, when the City of Salisbury prepared and approved the initial concept of developing 42 ha of low-lying saline land into a stormwater detention basin and wetlands habitat. After Council approval in 1989, Stage 1 (25 ha) was completed in 1990, Stage 2 (12 ha) in 1993 and the largest stage, Stage 3 (72 ha) in 1995. The 114 ha area of land, including the wetlands, has become home to over 160 species of birds, eight species of fish, four species of frog, yabbies, long-necked tortoise and numerous aquatic invertebrates along with more than 25 species of aquatic plants.

As well as the environmental and social benefits arising from the adoption of stormwater retention in wetlands and the associated use of ASR, the Salisbury Council has also extended the use of conserved urban stormwater as a commercial enterprise. In 2001, the City of Salisbury established a project partnership to construct wetlands and ASR facilities to treat and store stormwater at Parafield Airport, Adelaide's secondary airport, and provide over 1×10^6 $m^3 \cdot year^{-1}$ to G. H. Michell & Sons Australia Pty Ltd, Australia's largest wool processor. The project's capital cost was $4.5 million, with initial funding support of AUD $1.387 million through the Commonwealth's Environment Australia Urban Stormwater Initiative, AUD $1million from GH Michell & Sons Australia, AUD $140 000 from the Northern Adelaide Plains Barossa Catchment Water Management Board, an in-kind contribution of AUD $40 000 from the then SA Department of Water Resources, with the balance being funded by the City of Salisbury [11]. The Michell company was the first major external customer.

Considering all capital and operating costs and allowing for aquifer losses, the cost of supply in 2012/13 was determined to be AUD$1.57 m^{-3} for non-potable water and AUD$1.96 to $2.24 m^{-3}, were it to be used for potable water (excluding cost of mains distribution). These cost compared favorably with the retail price of mains water at that time of AUD$3.45 m^{-3}. Costs of supply of non-potable water through new third-pipe systems were similar to or exceeded the costs of mains water [12].

In 2010 the Council established the Salisbury Water Business Unit, with a governance Board comprising external experts from the water industry, finance and law, to operate and maintain the various water harvesting and supply schemes. The water business now supplies over 500 external customers, including 31 schools, and Michell remains one of the key customers.

3 Water quality results for non-potable water supplies of stormwater origin

The Parafield scheme involves diversion of stormwater via a weir in the Parafield Drain, which is one of the main stormwater catchment channels within the Council area. Water is diverted to a 50,000 m^3 capacity 'in stream' capture basin. It is then pumped to a similar capacity holding basin, from where flow is controlled to a two hectare reed bed planted with *Phragmites* and *Typha* vegetation. It flows continuously through the densely planted reed bed to biologically cleanse the water. The residency period of the water in the treatment ponds prior to being stored in the aquifer using ASR, is typically between seven and ten days, depending on inflow water quality [13].

Pollutant loads for traditional stormwater hazards are significantly reduced, e.g. suspended solids (77%); *E. coli* (65%); total nitrogen (65%); total phosphorous (76%) total lead (86%) and total zinc (81%) [13]. Organic pollutant removal of a number of trace organics, notably pesticides and herbicides was evaluated using diffusion cells and also found to be significant [14]. The treatment ponds are netted to discourage bird life and the risk of bird strikes on nearby aircraft. With advantage for the wool company's processing, the treated stormwater arrives at the wool processing plant at 200–250 ppm total dissolved solids, substantially lower than the potable water it replaced, ASR being used to balance supply and demand. The entire system is illustrated in Fig. 1.

Fig. 1 Layout of Parafield Airport Wetlands and MAR wells

This water is also used to provide a supply of recycled water to the nearby suburb of Mawson Lakes which has a population of 10,000 residents, 10,000 daily incoming workers and 5,000 students in an adjacent campus of the University of South Australia. There is a mandate at Mawson Lakes for benchmarking innovations including water cycle management and an energy conservation system. Land titles have an encumbrance requiring installation in the houses at the time of construction of dual (“third pipe”) water supply systems with purple pipes and taps for non-potable reclaimed water in addition to the normal potable mains. Installation of the dual water supply system must conform to the *South Australia Reclaimed Water Guidelines*. The distributed recycled water is sourced from a combination of stormwater from the Parafield Airport wetlands and remediated wastewater from the nearby Bolivar Sewage Treatment Plant which uses dissolved air, flotation, filtration (DAFF) technology, The two water sources are brought together in a large 26,000 m^3 mixing tank prior to final disinfection and distribution through the purple pipe reclaimed water supply system. The water can be used for toilet flushing, garden watering, and car washing, and over summer, also supports the numerous lakes featured in the suburb. The stormwater serves to dilute the total dissolved salts of the treated wastewater, to enable irrigation of salt-intolerant garden plants.

As part of its water business, a ring main was built to link nine of the Council’s harvested water sources from its principal wetlands to ensure the continuity of supply from the Council’s stormwater resources to the community. A risk-based Management Plan underpins the operation of Council’s stormwater business [15]. The principal stormwater harvesting schemes are summarized in Table 1, and their geographical distribution is shown in Fig. 2.

The urban proportion of catchments was calculated from the summed area of industrial, institutional, recreational, residential and roads/rail land use classes divided by the total catchment area. Land use data were sourced from the South Australian Department of Planning and Local Government as of June 30th 2011 [18].

Water is not extracted from the Greenfields aquifer storage scheme and does not contribute to the Salisbury ring main. However, water injected at Greenfields is used to transfer water allocation credits to allow extraction at other sites. The current Salisbury Development Plan continues to include specific requirements for Water Sensitive Design, Water Catchment Areas and conservation of Biodiversity and Native Vegetation [19]. All industrial, commercial and multi-unit residential developments that had implications for stormwater management were 100% compliant with WSUD principles in 2014–2015 and.2015–2016 [20]

There are significant environmental and flood mitigation benefits through harvesting and treating stormwater from the Council’s catchments in terms of protecting Barker Inlet, an estuary into which Salisbury’s stormwater otherwise flows. This estuary is an essential fish breeding ground and nursery for much of the State’s fisheries. This

Table 1 Salisbury stormwater harvesting schemes [16]

site name	year injection commenced	catchment area/ha	% urban area	estimated annual yield /($\times 10^6$ m^3)
Parafield ASR	2003	1,590	73	1.1 [a]
Cobbler Ck./ Bridgestone Park	2016	1,017	38	
Unity Park ASR	2006	5,116	77	1.3 [b]
Paddocks ASR	2000	456	89	0.1 [b]
Greenfields ASR	2008	11,371	71	0.3 [b]
Edinburgh South ASR	2012	4,417	61	1.2 [a]
Kaurna Park ASR	2005	5,512	64	0.6 [b]
Whites Road ASR	2014	2,628	61	1.2 [a]
total		32,107		5.8

Note: [a] Design capacity [b] Based on July 2009 to December 2011 injection volumes

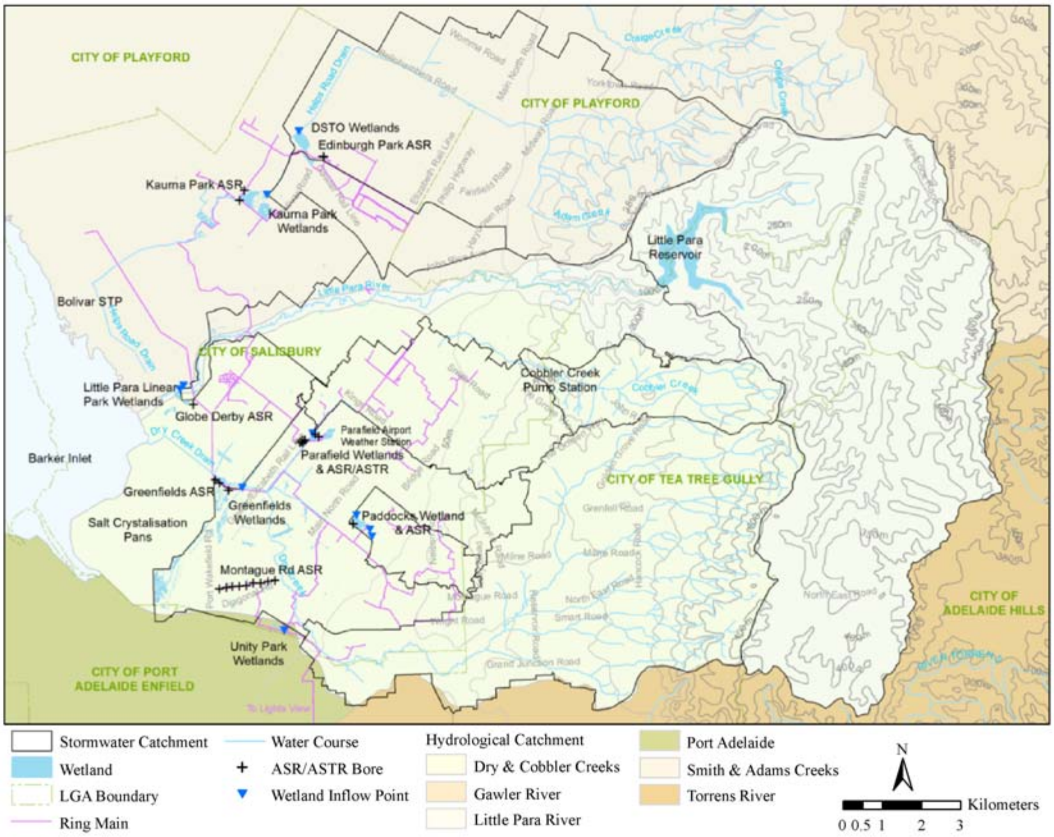

Fig. 2 Salisbury stormwater harvesting catchments and MAR schemes shown in relation to Little Para Reservoir and hydrological sub-catchments Dry and Cobbler Creeks, Little Para River, Smith and Adams Creeks [17]

inlet also supports an abundance of wildlife in its diverse range of habitats [21]. There were no storm events (greater than 25 $\mathrm{mm \cdot hour^{-1}}$) that bypassed or overflowed the wetland systems in 2014–2015 but two such events occurred in 2015–2016 [20].

The Water Business generated over AUD$ 2.8 million in external revenue in 2015–2016 [20]

4 Evaluating stormwater quality for alternative uses including potable water supply

From about 2000, Australia entered a prolonged period of what came to be known as the “millennium drought.” This encouraged the urgent adoption of alternative water sources and led nationally to the rapid construction of five sea water desalination plants and three wastewater advanced water recycling plants in various capital cities of Australia [22]. Most capital cities had severe water restrictions. Adelaide, had for 50 years been supplementing its catchment-based drinking water supplies by pumping water across the Mount Lofty Ranges from the River Murray, the principal river in southern Australia, to Adelaide’s water storages. In some dry years, this constituted up to 80 per cent of supply. However, toward the end of the millennium drought, the salinity of the River Murray reached a level that was no longer suitable for drinking purposes [23]. This led to investigating a Managed Aquifer Recharge and Stormwater Reuse Options project designed to evaluate the suitability of water from the Salisbury Council Schemes for a variety of uses including drinking [24]. A set of aquifer storage, transfer and recovery (ASTR) experimental bores involving injection through one set of bores, transfer laterally within the aquifer and recovery from another set of bores was installed. Any additional treatment that might be required was also evaluated. Qualitative and quantitative water (quality) risk assessments were performed based on water from the combined Salisbury ring main and associated stormwater harvesting systems with a detailed focus on the Parafield Airport stormwater harvesting scheme. Twelve configurations for three different end uses were evaluated – four for open space irrigation, four for use in dual reticulation “purple pipe” systems for toilets, washing machines, car washing and garden use, and four for indirect potable reuse with and without managed aquifer recharge, or with intermediate treatment and reservoir storage before the final water treatment plant for drinking water supply. The risk assessment utilized catchment land use and water quality data [25,26] to evaluate the risks to human health and the environment for the three targeted end uses [23,27]. It considered treatment processes required in order to meet those uses according to the most relevant Australian and International guidelines [2,28].

5 Stormwater source reliability

The reliability of stormwater supplies was assessed [29] and revealed the relative resilience of urban stormwater supplies in drought and under a changing climate with respect to surface water resources generated in rural catchments. This is due to the high and increasing proportion of impervious area in urban catchments, restricting evapotranspiration and infiltration, and the ability to store and recover large volumes of water in an aquifer, even a brackish one.

6 Catchment land-use risks

A detailed geographical information system based stormwater catchment land use analysis was developed to assess stormwater quality risks. Catchment land use risk assessment methods used were consistent with those described for drinking water catchments in WHO Guidelines and the results refined through a series of project stakeholder workshops which included representatives from the South Australian Water Corporation, South Australian Department for Environment, Water and Natural Resources, the City of Salisbury, the University of South Australia and representatives from similar sites in Singapore, Melbourne, Geelong, Orange and Brisbane. All stormwater catchments were dominated by residential and commercial land uses. Sewer overflows, which represented the highest risks for pathogens, were also mapped in the urban catchments [25]. Catchment land uses are illustrated in Fig. 3.

7 Microbiological risks

Targeted stormwater event-based monitoring of adenovirus, *Cryptosporidium* and *Campylobacter*, the human health reference pathogens of viruses, protozoa and bacteria, respectively, was undertaken to determine numbers prior to water recycling via an aquifer. This allowed the determination of a 95th percentile of reference pathogen numbers in stormwater (2 $\mathrm{n \cdot L^{-1}}$ for adenoviruses, 1.4 $\mathrm{n \cdot L^{-1}}$ for *Cryptosporidium* and 11 $\mathrm{n \cdot L^{-1}}$ for *Campylobacter*) and was used in a quantitative microbial risk assessment to determine the required microbial inactivation targets [25]. Based on a quantitative microbial risk assessment, the capacity to meet health standards was determined [27], Open space irrigation requires 1.6 $\log_{10}$ reduction for viruses, 0.5 $\log_{10}$ for protozoa and 1.2 $\log_{10}$ for bacteria. These standards have been met for some years. A dual reticulation system using purple pipes which include potential exposure through toilet flushing and washing machine use requires 2.7 $\log_{10}$ reduction for viruses, 1.6 $\log_{10}$ for protozoa and 2.3 $\log_{10}$ for bacteria. It was considered that aquifer treatment could potentially deliver this treatment if it were validated. Page *et al.* reported that 1.0 – 2.0 $\log_{10}$ removal for E.coli across the different Salisbury ASR systems [23]. Alternatively UV disinfection could be required in addition to chlorination for protection of the distribution system, chlorination being ineffective for protozoa. Drinking water requires 5.8 $\log_{10}$ for viruses, 4.6 $\log_{10}$ for protozoa and 5.3 $\log_{10}$ for bacteria as a health-based target and would require appropriate post-extraction water treatment for which several options could be considered [16]. In spite of variations in health and environmental risk-related water quality parameters between rainfall events at this and other Australian and international sites where stormwater quality had been assessed, there was surprising uniformity in the 95th percentile values of stormwaters internationally [26]. The 95th percentiles of iron, turbidity, color and faecal indicators exceeded the drinking water guideline values at all sites. Likewise, measured hazards for which 95th percentile values met drinking water guidelines (other metals [e.g. zinc], salinity [electrical conductivity] and nutrients including nitrate) did so at all sites. Considering a variety of climatic zones and catchment characteristics and the temporal variations typical in urban stormwater quality, there was a remarkable similarity in the 95th percentile concentrations for a suite of water quality hazards in urban stormwater. This is important in consideration of drinking water risk assessments and determining treatment requirements for potable use. This demonstrated that the Salisbury catchment was fairly typical in relation to data from international studies [26] and found to be consistent with respect to these parameters that exceeded or met the World Health Organisation guidelines for drinking water quality [28].

For open space irrigation, unacceptable maximum risks were associated with pathogens. For “purple pipe” non-potable use, additional unacceptable risks were associated with aesthetic quality (principally color) and salinity. For drinking water use, further unacceptable maximum risks were associated with inorganic chemicals. The results indicated a degree of uniformity in the stormwater catchments connected to the managed aquifer recharge (ASR) sites which fed into the ring main system for supply of harvested stormwater by the City of Salisbury.

8 Residual risks

From that information, it was possible to derive geographical risk assessment maps for pathogens to public health,

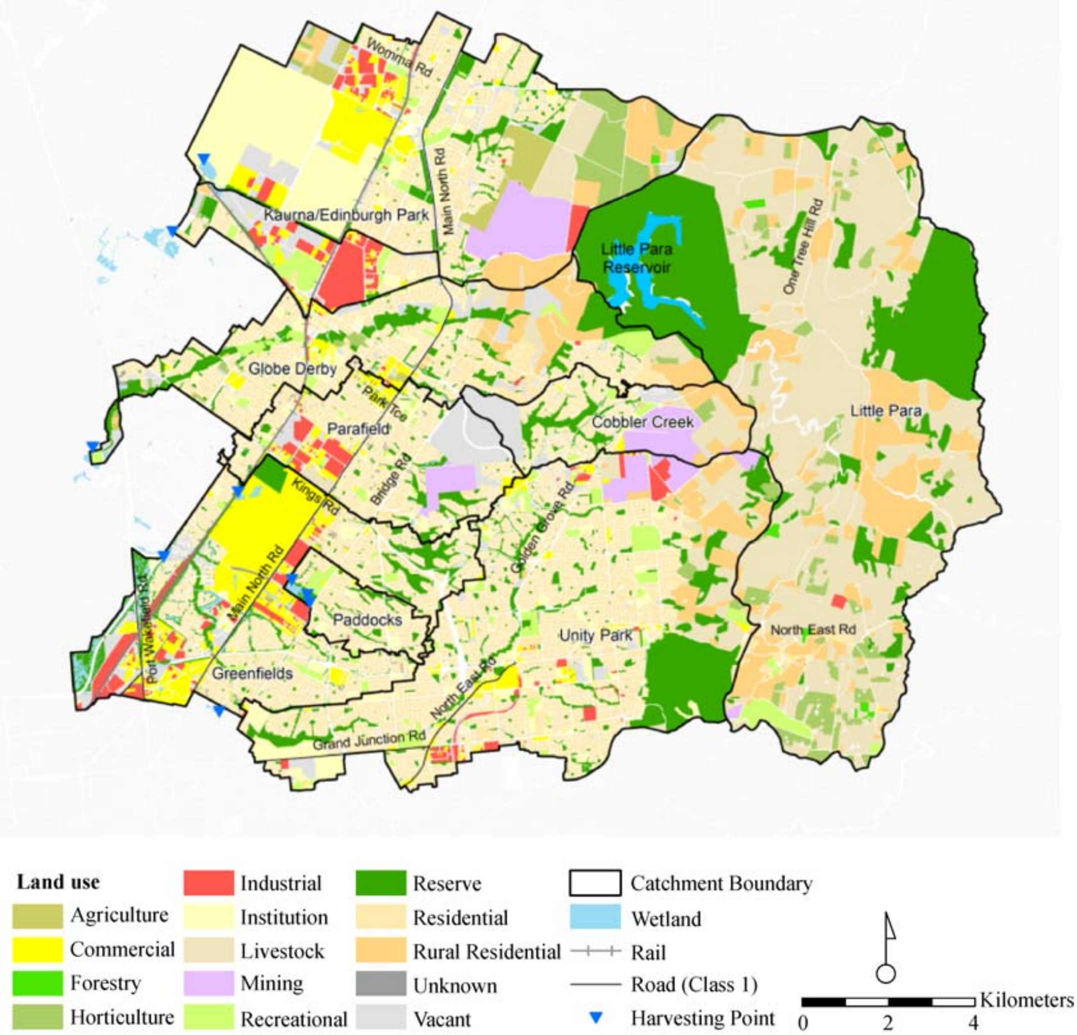

Fig. 3 Catchment land uses related to Salisbury stormwater harvesting and reuse schemes [17]

and risks of inorganic and organic chemicals, nutrients and turbidity to human health and the environment. Based on measured water quality and the series of existing and proposed pollutant barriers, residual risks to human health from chemicals, nutrients and turbidity were assessed to be acceptably low. There were no inherent radionuclide risks identified in the catchment. There were no identified pathogen risks from the ambient groundwater which was in confined aquifers. However, water added through managed aquifer recharge may well generate risks, though they may be capable of attenuation. Some mobilised arsenic has been detected in the groundwater but can be managed by engineered drinking water treatment. An example of an inherent (unmitigated) risk map for stormwater, being that for the potential for organic chemicals to impact on environmental receptors, is given in Fig. 4. Here the highest risk relates to use of pesticides and herbicides and accidental spills of petroleum hydrocarbons and industrial chemicals. Water quality monitoring data (where available) were collected across the entire system and related to hazards associated with the 12 stormwater use options. These water quality data included from the catchment/ wetland inlets; wetland outlets; aquifer recovered water sources; recycled stormwater distribution pipelines; and from the blended recycled water at Mawson Lakes.

From the extensive data presented by Page et al. [16], it was concluded that under the Australian Water Recycling Guidelines, a pathogen attenuation credit of up to 4 $\log_{10}$ could potentially be assigned to an ASTR system (separate injection and recovery wells) but a suitable validation scheme would need to be developed. While fresh water recovery was successful, the rate of inactivation of cryptosporidium and viruses measured using diffusion cells with PCR quantification, was lower than forecast, likely due to low temperatures of injected water (8°C–12°C) [30]. Therefore if this water were to be recovered for potable use, and in the absence of data on net attachment of pathogens to the aquifer matrix and

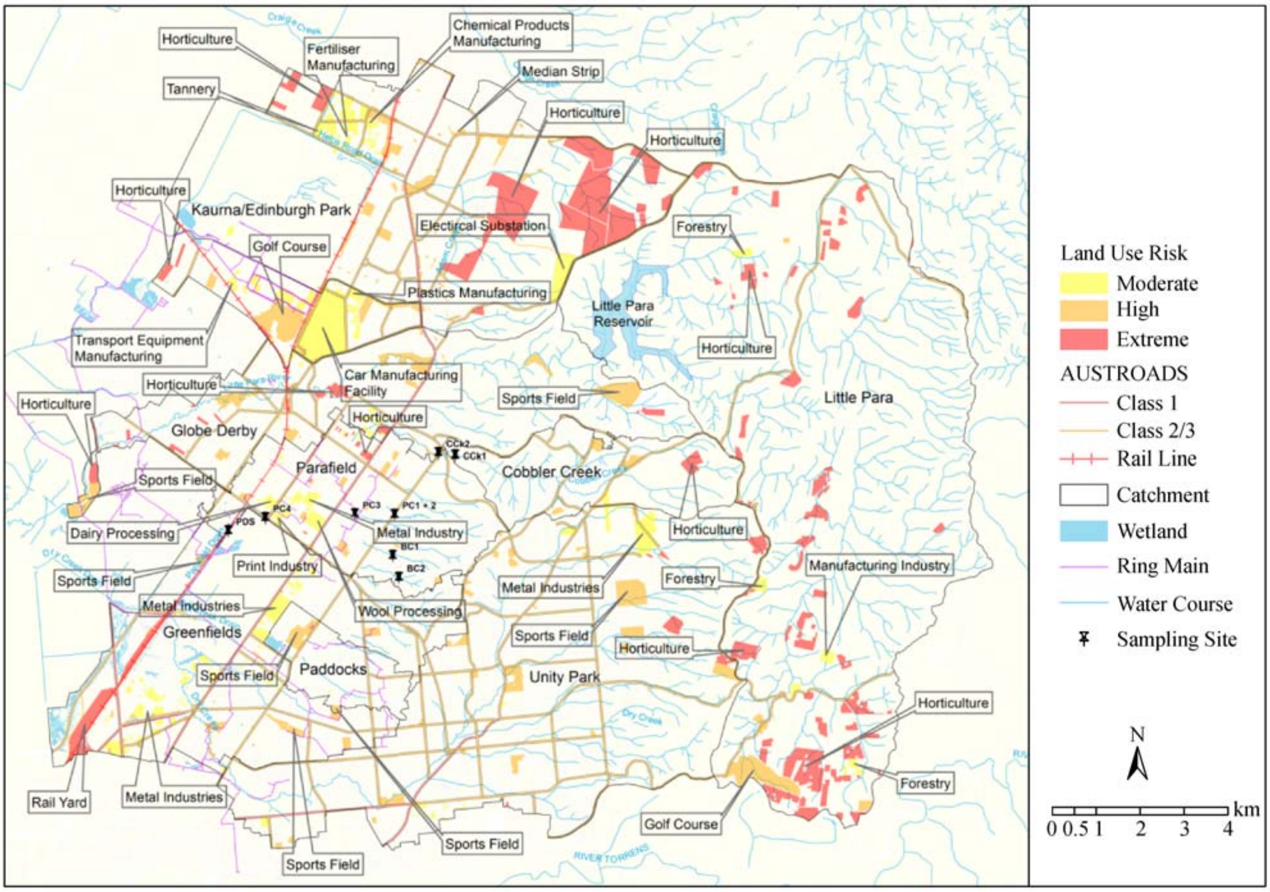

Fig. 4 Catchment land use organic chemical environmental risks [15]

infectivity, conventional disinfection would still be required. Until that research is done the cost of ASTR is uncompetitive with ASR plus conventional disinfection for potable use. Hence the ASTR wells are now all utilized as operational ASR wells for the Parafield scheme. In addition, the detention time in the aquifer would need to be quantified historically and a commitment to the management of detention times evident. The ASR system (injection and recovery using the same well) as currently operated did not guarantee a suitably long residence time in the subsurface. This highlights the potential advantages of longer detention and aquifer travel times in the ASTR system for water treatment if pathogen attachment and inactivation (e.g., [31]) is considered.

From the other water quality parameters assessed, including inorganic chemicals, organic chemicals, nutrients, turbidity, salinity and radionuclides, it was found that in the majority of cases, the aquifer recovered water quality met most WHO Drinking Water Guideline health criteria. Aesthetic quality targets were occasionally exceeded e.g. high color due to high iron concentrations in the recovered water caused by dissolution of iron in the aquifer sediments, occasional turbidity spikes and high salinity caused by excessive entrainment of brackish groundwater in recovered water. The residual risks to human health were assessed for each of the 12 options. Risks were found to be acceptable and could meet health-based and aesthetic water quality targets with appropriate treatment and controls for each of the end uses of recovered water. Treatment for pathogens, turbidity and color particularly were required prior to third pipe and drinking water use. Further assessments were performed and summarized [24], concerning public acceptance of harvested stormwater for drinking, water quality changes within stormwater pipe distribution systems, risk management plans and their subsequent auditing [32], and economic assessment of all options.

The MAR systems have been operating for a number of years and recycled stormwater has been similarly used for open space irrigation and blending with treated wastewater in third pipe systems. The risk assessment verified that risks to the environment were well managed. Monitoring results also indicated that there would be minimal risks to the environment for the drinking water options. In addition to meeting water quality requirements for human health and the environment, a water safety plan would need to be fully implemented and accepted by stakeholders, regulators and the community to ensure the risks were managed on an ongoing sustainable basis. However, it was demonstrated that water from the Salisbury stormwater reclamation wetlands has potential to meet drinking water standards with appropriately added end-point water treatment [17].

9 Conclusions

Over a period of 50 years, as the City of Salisbury has evolved from a small country village into a major suburban center, it has adopted a thoughtful approach to adapting and maximising the benefits for urban amenities from the changes that have occurred in its water cycle following urbanisation. It has managed stormwater flooding risks and generated a water business from the stormwater harvesting. Its success has contributed motivation for the establishment of Water Sensitive SA [33] to encourage capacity building in the concepts of WSUD/LID/ "sponge city." (Details and photographs of the City of Salisbury's WSUD systems can be accessed by interactive map from this Water Sensitive SA website.) The associated research has had important flow-on effects for the City of Salisbury, opening up market opportunities in the high volume, high quality food processing sector. The research also identified significant changes in public attitudes to recycled stormwater, which in time and with ongoing research, may facilitate its use to supplement drinking water supplies. This is truly a long-term example of successful adaptation of low impact, water sensitive urban design on a broad scale in the creation of a major urban environment where only a few years ago there was open farm land used for dryland cereal production.

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References

1. Commonwealth of Australia Constitution Act 1900(Imp) constituting the Commonwealth of Australia. http://www.austlii.edu.au/au/legis/cth/consol_act/coaca430/ (accessed January 13 2017)
2. NWQMS National Water Quality Management Strategy. 2015, https://www.environment.gov.au/water/quality/national-water-quality-management-strategy (accessed 10 February 2016)
3. NRMMC. EPHC and NHMRC. Australian Guidelines for Water Recycling, Managing Health and Environmental Risks, Volume 2C-Managed Aquifer Recharge. Natural Resource Management Ministerial Council, Environment Protection and Heritage Council National Health and Medical Research Council, 2009, 237pp. http://www.environment.gov.au/water/quality/publications/nwqms-australian-guidelines-water-recycling-managing-health-phase2-aquifer-recharge (accessed 24 February 2016)
4. Clar M. State of the LID/GSI Practice: Perspectives from the ASCE-EWRI-LID/GSI National Committee, LID 2016 Conference, Beijing, Paper 336
5. CoAG. Intergovernmental Agreement on the National Water Initiative, 2004. http://nwc.gov.au/__data/assets/pdf_file/0008/24749/Intergovernmental-Agreement-on-a-national-water-initiative.pdf (accessed 10 February 2016)
6. JSCWSC. Evaluating options for Water Sensitive Urban Design – a National Guide, Joint Steering Committee for Water Sensitive Cities, 2009, Department of Environment, Water, Heritage and the Arts, Canberra, Australia. https://www.environment.gov.au/resource/evaluating-options-water-sensitive-urban-design-%E2%80%93-national-guide (accessed 10 February 2016)
7. City of Salisbury. Our History, 2016. http://www.salisbury.sa.gov.au/Council/About_our_City_of_Salisbury/Our_History (accessed 10 February 2016)
8. Hains S. Stormwater: Towards Water Sensitive Cities, Local Government Managers Association Congress, 2009, Darwin, Australia. www.salisbury.sa.gov.au/.../watersensitivecities-paper.pdf (accessed 10 February 2016)
9. Hutchings A, Garnaut C. The Private Development Company and the Building of Planned Communities in Post-war South Australia: Reid Murray Developments, Reality Development Corporation and their successors. Journal of the Historical Society of South Australia, 2012, 40: 96–116
10. City of Salisbury. Wetlands locations. 2015. http://www.salisbury.sa.gov.au/Live/Environment_and_Sustainability/Wetlands_and_-Water/Wetlands/Wetlands_Locations (accessed 10 February 2016)
11. Radcliffe J C. Water Recycling in Australia 2004, Australian Academy of Technological Sciences and Engineering, Melbourne
12. Dandy G, Ganji A, Kandulu J, Hatton MacDonald D, Marchi A, Maier H, Mankad A, Schmidt C E. (2014). Goyder Institute for Water Research Technical Report Series No. 14/1, Adelaide, South Australia. ISSN: 1839–2725. http://goyderinstitute.org/index.php?id=20 (accessed 18 Jan 2017)
13. Page D, Barry K, Pavelic P, Dillon P, Chassagne C. Preliminary quantitative risk assessment for the Salisbury stormwater ASTR project, 2008, Water for a Healthy Country National Research Flagship Report. http://www.clw.csiro.au/publications/waterforahealthycountry/2008/wfhc-Salisbury-ASTR-HACCP.pdf (accessed 17 January 2017).
14. Page D, Miotliński K, Gonzalez D, Barry K, Dillon P, Gallen C. Environmental monitoring of selected pesticides and organic chemicals in urban stormwater recycling systems using passive sampling techniques. Journal of Contaminant Hydrology, 2014,

158: 65–77

15. Page D, Gonzalez D, Naumann B, Dillon P, Vanderzalm J, Barry K. Stormwater Managed Aquifer Recharge Risk-Based Management Plan, Parafield Stormwater Harvesting System, Stormwater supply to the Mawson Lakes Recycled Water Scheme, Industrial Uses and Public Open Space Irrigation, 2013, Goyder Institute for Water Research Technical Report 13/18, Adelaide, South Australia
16. Page D W, Vanderzalm J L, Barry K E, Torkzaban S, Gonzalez D, Dillon P J. Dillon, P J. *E. coli* and turbidity attenuation during urban stormwater recycling via Aquifer Storage and Recovery in a brackish limestone aquifer. Ecological Engineering, 2015, 84: 427–434
17. Page D, Gonzalez D, Dillon P, Vanderzalm J, Vadakattu G, Toze S, Sidhu J, Miotlinski K, Torkzaban S, Barry K. Managed Aquifer Recharge Stormwater Use Options: Public Health and Environmental Risk Assessment Final Report, Goyder Institute for Water Research 2013, Technical Report 13/17, Adelaide, South Australia
18. DPLG. 2011, Spatial Data Download. http://www.planning.sa.gov.au/ Department of Planning and Local Government, Adelaide, South Australia (accessed 4 June 2011)
19. DPTI. 2016, Development Plan, Salisbury Council, Consolidated to 7 January 2016. Department of Planning Transport and Infrastructure, Adelaide, South Australia, (617pp)
20. City of Salisbury – Annual Reports. http://www.salisbury.sa.gov.au/Council/Council_Plans_and_Documents/City_Management_Plans/Annual_Report (accessed 19 January 2017)
21. Pitman C. Stormwater harvesting and utilisation. Water Recycling Australia, 2nd National Conference 2003, Brisbane. Australia.
22. Radcliffe J C. Water recycling in Australia – during and after the drought. Environmental Science Water Research & Technology, 2015, 1(5): 554–562
23. Page D, Gonzalez D, Sidhu J, Toze S, Torkzaban S, Dillon P. Assessment of treatment options of recycling urban stormwater recycling via aquifers to produce drinking water quality. Urban Water Journal, 2016, 13(6): 657–662
24. Dillon P. Page D, Dandy G, Leonard R, Tjandraatmadja G, Vanderzalm J, Rouse K, Barry K, Gonzalez D, Myers B. Managed Aquifer Recharge Stormwater Use Options: Summary of Research Findings, Goyder Institute for Water Research, 2014, Technical Report 14/13. http://goyderinstitute.org/index.php?id = 20 (accessed 24 February 2016)
25. Page D W, Barry K, Gonzalez D, Keegan A, Dillon P. Reference pathogen numbers in urban stormwater for drinking water risk assessment. Journal of Water and Health, 2016, 16(1): 30–39
26. Page D, Vanderzalm J, Dillon P, Gonzalez D, Barry K. Stormwater quality review to evaluate treatment for drinking water supply via managed aquifer recharge. Water, Air, and Soil Pollution, 2016, 227 (9): 1–16
27. Page D, Gonzalez D, Torkzaban S, Toze S, Sidhu J, Miotliński K, Barry K, Dillon P. Microbiological risks of recycling urban stormwater via aquifers for various uses in Adelaide, Australia. Environmental Earth Sciences, 2015, 73(12): 7733–7737
28. WHO Guidelines for Drinking-Water Quality. 4th Edn. 2011, World Health Organisation, Geneva, Switzerland. http://whqlibdoc.who.int/publications/2011/9789241548151_eng.pdf?ua = 1 (accessed 1 November 2016)
29. Clark R, Gonzalez D, Dillon P, Charles S, Cresswell D, Naumann B. Reliability of water supply from stormwater harvesting and managed aquifer recharge with a brackish aquifer in an urbanising catchment and changing climate. Environmental Modelling & Software, 2015, 72: 117–125
30. Sidhu J P S, Toze S, Hodgers L, Shackelton M, Barry K, Page D, Dillon P. Pathogen inactivation during passage of stormwater through a constructed reedbed and aquifer transfer, storage and recovery. Water Science and Technology, 2010, 62(5): 1190–1197
31. Sidhu J P, Toze S, Hodgers L, Barry K, Page D, Li Y, Dillon P. Pathogen decay during Managed Aquifer Recharge at four different sites with different geochemical characteristics and recharge water sources. Journal of Environmental Quality, 2015, 44(5): 1402–1412
32. Stevens D. Audit of the Parafield Stormwater Harvesting and Managed Aquifer Recharge System for Non- Potable Use against the Stormwater Risk- Based Management Plan. Goyder Institute for Water Research 2014, Occasional Paper Series No. 14/1. http://www.goyderinstitute.org/uploads/Goyder-RBMP%20Audit_Final.pdf (accessed 24 February 2016)
33. Water Sensitive S A. http://www.watersensitivesa.com/ (accessed 18 Jan 2017)