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Sharma, Ashok, Pezzaniti, David, Myers, Baden, Cook, Stephen, Tjandraatmadja, Grace, Chacko, Priya, Chavoshi, Sattar, Kemp, David, Leonard, Rosemary, Koth, Barbara and Walton, Andrea (2016) Water Sensitive Urban Design: An Investigation of Current Systems, Implementation Drivers, Community Perceptions and Potential to Supplement Urban Water Services. Water, 8 (7). ISSN 2073-4441 *water*

MDPI

Article

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Ashok K. Sharma [1,2,*], David Pezzaniti [3], Baden Myers [3], Stephen Cook [2], Grace Tjandraatmadja [2], Priya Chacko [4], Sattar Chavoshi [3], David Kemp [3], Rosemary Leonard [5], Barbara Koth [3] and Andrea Walton [6]

1 Institute of Sustainability and Innovation, College of Engineering and Science, Victoria University, Melbourne, VIC 3000, Australia

2 CSIRO Land and Water, Research Way, Clayton, VIC 3168, Australia; Stephen.Cook@csiro.au (S.C.); gracetjand@gmail.com (G.T.)

3 University of South Australia, Mawson Lakes Campus, Adelaide, SA 5095, Australia; David.Pezzaniti@unisa.edu.au (D.P.); Baden.Myers@unisa.edu.au (B.M.); Sattar.Chavoshi@unisa.edu.au (S.C.); David.Kemp@unisa.edu.au (D.K.); Barbara.Koth@unisa.edu.au (B.K.)

4 CSIRO Land and Water, Waite campus, Glen Osmond, SA 5064, Australia; priyachacko79@gmail.com

5 CSIRO Land and Water Flagship, Floreat Campus, Floreat, WA 6913, Australia; Rosemary.Leonard@csiro.au

6 CSIRO Land and Water Flagship, ESP, Dutton Park, QLD 4102, Australia; Andrea.Walton@csiro.au

* Correspondence: ashok.sharma@vu.edu.au or asharma2006@gmail.com; Tel.: +61-3-9919-4519

Academic Editor: Brigitte Helmreich

Received: 9 May 2016; Accepted: 20 June 2016; Published: 28 June 2016

Abstract: Large scale centralised water, wastewater and stormwater systems have been implemented for over 100 years. These systems have provided a safe drinking water supply, efficient collection and disposal of wastewater to protect human health, and the mitigation of urban flood risk. The sustainability of current urban water systems is under pressure from a range of challenges which include: rapid population growth and resulting urbanisation, climate change impacts, and infrastructure that is ageing and reaching capacity constraints. To address these issues, urban water services are now being implemented with Integrated Urban Water Management (IUWM) and Water Sensitive Urban Design (WSUD) approaches. WSUD systems can deliver multiple benefits including water conservation, stormwater quality improvement, flood control, landscape amenity and a healthy living environment. These systems can be provided as stand-alone systems or in combination with centralised systems. These systems are still novel and thus face knowledge gaps that are impeding their mainstream uptake. Knowledge gaps cover technical, economic, social, and institutional aspects of their implementation. This paper is based on the outcomes of a comprehensive study conducted in South Australia which investigated impediments for mainstream uptake of WSUD, community perceptions of WSUD and potential of WSUD to achieve water conservation through the application of alternative resources, and in flood management. The outcomes are discussed in this paper for the benefit of water professionals engaged with WSUD planning, implementation, community consultation and regulation. Although the paper is based on a study conducted in South Australia, the comprehensive framework developed to conduct this detailed study and investigation can be adopted in any part of the world.

Keywords: water sensitive urban design; decentralised systems; water conservation; water quality; flood mitigation; sustainability

1. Introduction

The Water Sensitive Urban Design (WSUD) is supported by an underlying value of providing urban water services in a manner that considers the site specific opportunities and limitations of a development to provide water services in a way that protects and enhances local hydrological and ecological integrity. WSUD considers all aspects of the urban water cycle as a valuable resource. Incorporating WSUD in urban developments can also improve resilience to reduced yield from conventional water supply catchments due to potential climate change impacts. WSUD is seen as a component of Integrated Urban Water Management (IUWM). IUWM promotes a coordinated planning approach to drinking water, wastewater and stormwater services that takes into consideration the broader implications of sustainable development, including: energy demand, greenhouse gas emissions, solid waste generation, nutrient losses, life cycle costs, and community acceptability. WSUD systems are also known as sustainable urban drainage systems (SUDS) in the United Kingdom [1], stormwater best management practices (BMPs) and low impact development (LID) in the USA [2,3], and is broadly represented within the term green infrastructure. Fletcher et al. [4] have described the history and evaluation of these and other terms in detail. Sharma et al. [5] presented a definition of decentralised systems, which was developed around the current recognition of the role of decentralised water, wastewater and stormwater systems in mitigating the environmental impact of urban developments. The definition also highlighted drivers for the implementation of decentralised systems which included: overcoming the limited capacity of local water and wastewater services, protecting sensitive environments, showcasing examples of sustainable development, water conservation, landscape amenity and promotion of innovation and technology. Such a definition and drivers for decentralised systems also aligns to the WSUD philosophy. Sharma et al. [6] also highlighted the key impediments to greater WSUD uptake including inadequacy and fragmentation of current governance, regulation and guidelines for WSUD; lack of skills and knowledge; potential for increased public health risk; and, poor financial incentives. Similarly, Sapkota et al. [7] has identified gaps in knowledge for the interactions between centralised conventional and alternative systems. Moglia [8] indicated that socio-technical and institutional factors should be considered when developing enabling environments for alternative systems. Alternative systems have a potential to reduce the load on resources and the environment [9–14].

The Australian Intergovernmental Agreement on a National Water Initiative incorporated the concepts of WSUD into its urban water reform agenda, and defined WSUD [15] as:

> "The integration of urban planning with the management, protection and conservation of the urban water cycle that ensures urban water management is sensitive to natural hydrological and ecological processes"

WSUD elements normally have multi-functional objectives, which can include flood mitigation, mains (piped) drinking water conservation, water quality improvement and landscape amenity. The tools and approaches applied to achieve WSUD objectives need to be locally adaptable to the specific site conditions and development objectives. In South Australia, the former Department of Planning and Local Government [16] developed the *Water Sensitive Urban Design Technical Manual*, which provided guidance for the implementation of 12 WSUD tools in the greater Adelaide region. These are shown in Table 1.

Table 1. The Water Sensitive Urban Design (WSUD) tools for adoption [16].

No.	WSUD Approach/Tools	No.	WSUD Approach/Tools
1	Demand reduction	7	Bioretention systems for streetscapes
2	Rain gardens, green roofs and infiltration systems	8	Swales and buffer strips
3	Rainwater tanks	9	Sedimentation basins
4	Pervious pavement	10	Constructed wetlands
5	Urban water harvesting/ reuse	11	Wastewater management
6	Gross pollutant traps	12	Siphonic roofwater systems

The tools listed above give an indication of the breadth of approaches that can be applied, according to local conditions, in achieving WSUD objectives in South Australia. These tools can be categorised as those targeted toward mains water conservation, minimising wastewater flow, management of stormwater quantity and quality, and/or flood mitigation.

This paper describes a methodology and its application for the investigation of impediments to the uptake of WSUD systems in Greater Adelaide, South Australia (population 1.2 million). The project also explored community perceptions of WSUD systems and the potential of WSUD to meet local objectives for water harvesting, stormwater quantity management and flood mitigation. Broad outcomes of this study have been included in this paper. Various task specific publications from this multi-activity large study have also been developed. The project has applied an evidence-based process to evaluate the effectiveness of WSUD in achieving implementation objectives, and to identify the knowledge gaps and other impediments that are hindering greater mainstream uptake of WSUD approaches in South Australia. The methodology presented in this paper will benefit water professionals across the globe engaged in the implementation of IUWM and WSUD approaches for sustainable urban water servicing. It will particularly benefit those interested to understand their harvesting and flood mitigation potential and the barriers to increased uptake of these systems.

2. Methodology

The study aimed to investigate the impediments in the mainstream uptake of WSUD approaches, to conduct a post implementation assessment of developments in the study area to check if design objectives were being met, to explore the community perception of WSUD system implementation, and to understand the potential of retaining or detaining alternative water resources for stormwater flow reduction and flood mitigation. A Project Reference Group composed of key stakeholders was formed. This group met at the beginning of the project and at six month intervals to provide input on project directions such as case study site selection and model scenarios, and to review project outcomes.

Figure 1 depicts the overall methodology and the interaction between various tasks/ sub-tasks including the information transfer between different components of the study. A brief description of the main four tasks is provided in the following text.

2.1. Development of an Inventory of WSUD Tools Implemented in South Australia and Associated Drivers for Their Adoption (Task 1)

To begin the project it was essential to understand the type of WSUD systems implemented in South Australia and drivers behind adopting specific WSUD approaches and systems. An inventory of WSUD systems for the region was prepared by contacting local councils and developers. By making direct contact, we were also able to determine the drivers for implementing these systems. A technical report of this activity was prepared for the benefit of local water professionals and service providers.

2.2. Post Implementation Assessment of Developments Designed with WSUD Systems and Consultation with Stakeholders Regarding Their Perceptions of the Impediments Faced (Task 2)

Post implementation assessment of selected developments was designed to investigate the extent that specific WSUD design objectives were being achieved. For developments where objectives were not likely to be met, the reasons that caused this to occur were explored. To understand impediments in the mainstream uptake of WSUD systems, extensive stakeholder consultation was undertaken. Interviews were conducted with developers, engineering consultants, local and state government agencies, representatives of water industry bodies and other stakeholders. A literature review was required to investigate previous research outcomes and identify knowledge gaps. Similarly a review of current local and interstate policies was proposed for a gap analysis. This review has been reported by Tjandraatmadja et al. [17].

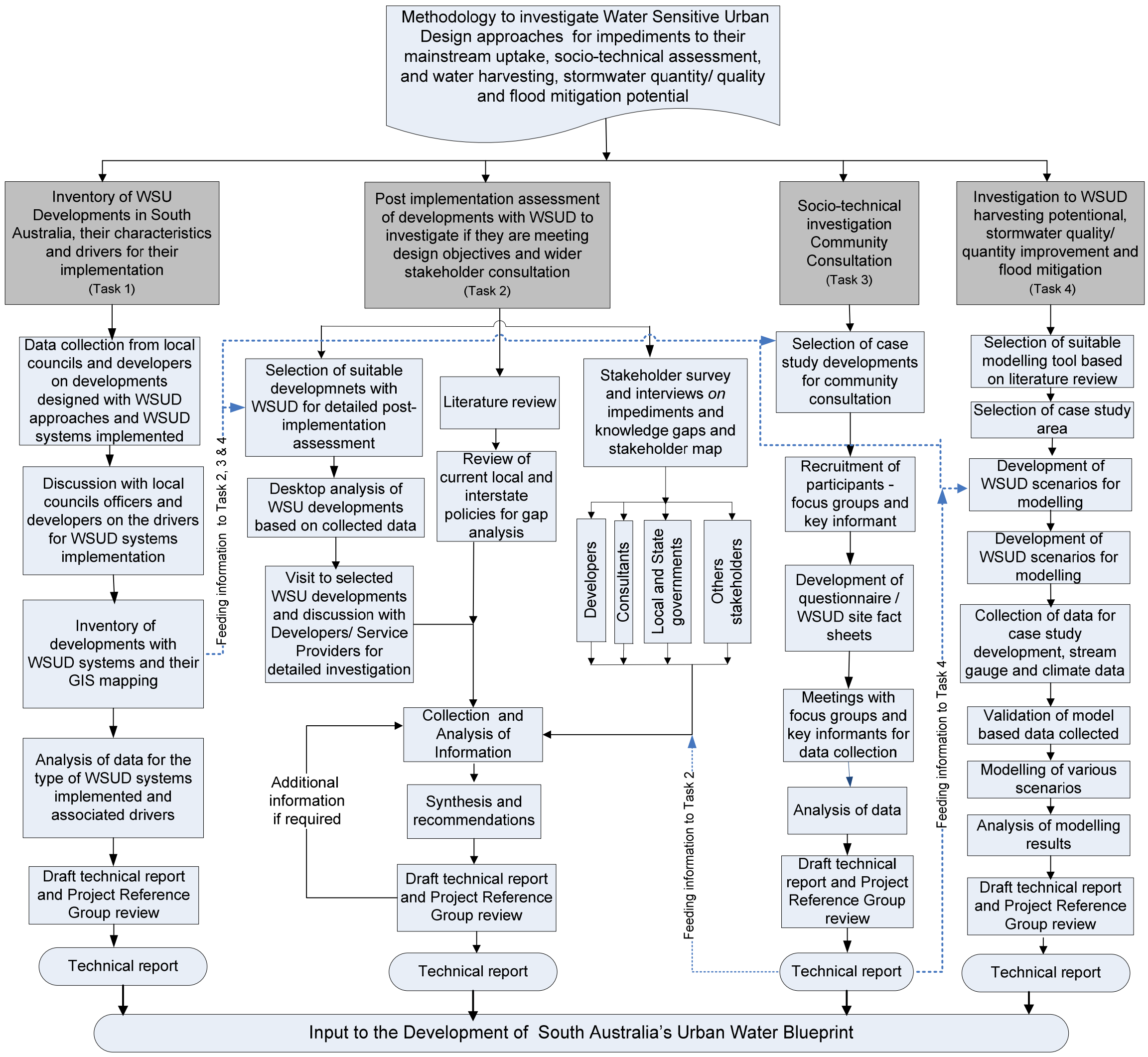

Figure 1. Flow diagram of the methodology adopted for investigation.

2.3. *A Community Consultation Process, Investigating the Social and Technical Impediments, Drivers and Opportunities for the Uptake and Management of WSUD Systems (Task 3)*

The community consultation aimed to investigate community perceptions of WSUD system implementation. The case study sites for community consultation were proposed to be selected from the inventory developed in Task 1, and on the basis of criteria to analyse a diversity of system types in the post implementation assessment of developments in Task 2. The principal data sources considered were focus groups with local residents and interviews with key informants (e.g., schools, residents associations, environmental groups, real estate agents, and other local businesses). A range of issues were included for information collection, such as perceived additional costs to the householder, perceptions of increased public health risk, issues associated with operation and management of WSUD elements, as well as residents' technical understanding of WSUD elements and their preference for different WSUD approaches. The information collected was then analysed qualitatively and documented in a technical report.

2.4. *Understanding the Potential of WSUD for Flood Control, Demand Management and Runoff Volume Reduction (Task 4)*

In this task, a suitable modelling tool was selected based on a literature review. A suitable case study site with observed flow data and landuse information was obtained and modelling scenarios identified based on feedback from Tasks 1 and 3. Modelling scenarios were based on the type of

WSUD systems adopted locally as per the inventory (See Section 3.1) and the community perceptions about different systems (See Section 3.3). Finally, a modelling approach for the scenario analysis was developed for assessment.

3. Application of the Methodology

Application of the methodology and broad outcomes of each of the four tasks conducted in this study are described in the following sections. As the study is quite large only an overview of this findings are presented here. Detailed outcomes from these tasks will be presented in other papers.

3.1. Development of an Inventory of WSUD Tools Implemented in South Australia and Associated Drivers for Their Adoption

3.1.1. Type of WSUD Systems Implemented

The inventory of developments with WSUD features in South Australia was developed through analysis of literature, online searches and consultation with local government, natural resource management boards and practitioners in South Australia [18]. This inventory was updated with additional information collected during the execution of the broader project [17]. For each WSUD development, the inventory detailed the site location, the name of the organisation responsible for operation, the rainfall zone in which it is located, the water sources being managed, the function or driver for the WSUD system, the development type and scale. A summary of WSUD systems based on the 220 sites identified is provided in Table 2 and the systems are listed based on their prevalence.

Table 2. Summary of WSUD systems.

No.	WSUD System	Numbers
1	Bioretention system sites (group installation streetscape)	192 (50 sites)
2	Wetland sites	82
3	Aquifer Storage and Recovery (ASR) sites	55
4	Infiltration only systems	30
5	Community wastewater management schemes	24
6	Projects incorporating harvesting and reuse	23
7	Permeable pavements	17
8	Wastewater reuse schemes	17
9	Green roofs	8 (5 sites)
10	Ponds	2

Table 2 demonstrates the prevalence of stormwater management features in Greater Adelaide, South Australia. The table shows that wetlands, bioretention systems, and infiltration systems are most prevalent. In terms of project numbers, WSUD systems that utilise local water sources to substitute mains water demand are dominated by stormwater reuse (20%) with wastewater recycling comprising only 4% of the project sample (disregarding volume of water supplied). Permeable paving, ponds and green roofs were the least commonly adopted WSUD features. At present, the vast majority of WSUD sites (76%) were retrofit projects built on existing public land by local government. The remaining WSUD schemes were located in greenfield residential areas (16%), commercial areas (6%) or associated with miscellaneous land uses (4%) [15].

3.1.2. Drivers for the Adoption of WSUD Approaches

Local water professionals were interviewed to understand the drivers for the uptake of WSUD approaches. The drivers reported ranged from the need for improved management of stormwater flows, improvement in water quality, the desire to reduce mains water consumption, reduction in financial costs and the need for preservation of local ecosystems or enhancing landscape amenity. Flow reduction, water conservation and water quality improvement were the most common drivers mentioned in 40%, 33% and 24% of sites, respectively. Multiple drivers were also mentioned for some WSUD sites. Most of practitioners interviewed at the local government level indicated that "to do the right thing" when the opportunity arose was a key driver. For example, several local governments included WSUD measures in conjunction with road or drainage upgrade works as the routine upgrade works allowed for an economically efficient incorporation of WSUD features into streetscape. Other key drivers that were perceived to have influenced the adoption of WSUD were the availability of funding opportunities, cost effectiveness in avoiding an infrastructure upgrade that was reaching capacity, role of WSUD in improved landscape amenity value, enabling policies and the existence of champions for WSUD adoption in local government.

3.2. Post Implementation Assessment of Developments Designed with WSUD Systems and Consultation with Stakeholders Regarding Their Perceptions of the Impediments Faced

3.2.1. Post Implementation Assessment of WSUD Developments

Based on the inventory of WSUD developments in South Australia, six case study sites (Table 3) were selected for more detailed assessment. The sites were selected on the basis of capturing a range of conditions across the following criteria: rainfall, alternative water sources, WSUD approaches used, development type and scale, the density of development, and availability of information on monitoring of developments. The selected sites incorporated a variety of WSUD approaches at varying scales of operation and with different management structures. A post implementation assessment was undertaken through the following activities: site visit, interviews with key people involved in the design and implementation of the WSUD elements, a desktop review of existing literature, and analysis of data relevant to WSUD performance (where available, e.g., water use metering, water quality monitoring). A brief overview of the case study sites in Greater Adelaide is provided in Table 3.

Table 3. WSUD sites for post implementation assessment.

Case Study Development	Development Type, WSUD Feature and Reason for Site Selection
Mawson Lakes Large outer suburban development, greenfield	Large scale mixed use development (10,000 pop.) with dual reticulation system to meet non-potable demand with recycled wastewater and stormwater; also a series of wetlands for stormwater treatment [19]. The development had the objective of reducing average annual household demand for potable water by 100 kL compared to an average Adelaide household
Lochiel Park Medium inner suburban development, infill	Medium scale (15 hectare) infill development with 106 dwellings in central Adelaide. Intended to provide a nationally significant example of Ecologically Sustainable Development (ESD), which included an objective of reducing potable water demand by 80% [20]. Provision of ASR scheme [21] and dual reticulation (separate pipe network for alternative water supply) to meet non-potable demand with stormwater, rainwater tanks for hot water demand, bioretention systems for stormwater treatment and a series of streetscape swales.
Springbank Waters Medium outer suburban development, greenfield	Part of a large stormwater harvesting project using an aquifer storage and recovery system. Large scale residential development (6000 pop.) with recycled stormwater used to irrigate public open space.
Mile End Street scale, suburban WSUD retrofit	Mile End is an established inner city suburb (4000 pop.). Raingardens have been retrofitted at street scale. Around 90 individual rain gardens installed in the area. Installed opportunistically during road replacement and kerb/gutter upgrades works.
Harbrow Grove Reserve Neighbourhood scale, suburban neighborhood park retrofit	Neighbourhood WSUD system comprises turf and rock swales, sedimentation pond, bioretention basin, detention basin and an underground rain vault to store treated stormwater runoff, which is then used for irrigation of the park. Data was availble for assessment for this development.
Christie Walk Small CBD development, infill	Demonstration of WSUD implementation at high density brownfield residential development (27 dwellings, 50 pop.). Rainwater and stormwater harvesting for non-potable supply system and green roof. It demonstrates a sustainable approach to urban development using the concept of an 'ecocity' [22].

Detailed assessment of the selected developments has been described by Tjandraatmadja et al. [17]. However, common findings from the post implementation assessment included:

- There was often a lack of a clear technical and economic justification for the implementation of WSUD systems. There is a need for improved understanding of how small-scale features may contribute to reducing peak and annual stormwater flows, and improving water quality, when retro-fitted across a catchment.

- The design intent of WSUD elements is often constrained by poor implementation by construction contractors. There is a need for those involved in the detailed and functional design of WSUD approaches to maintain oversight during the construction phase.
- Cost remains a barrier for the broader adoption of WSUD approaches. In many cases these schemes are financed under one-off capital funding opportunities to demonstrate more sustainable practices. It remains to be seen if the business case for some WSUD approaches is feasible without subsidies.
- Those WSUD schemes that receive funds for capital works often neglect to consider the ongoing costs and human resources (skills) needed for the operation and maintenance (O & M) of WSUD systems.
- There was reluctance from local councils to assume responsibility for the O & M of WSUD elements due to uncertainties on the cost burden compared to traditional approaches to water management.
- In many cases there has been no validation and monitoring of WSUD approaches, so there is no way of determining if they are achieving the sustainability objectives they were designed for.
- The multi-functionality of some WSUD elements (e.g., flood mitigation, stormwater management, alternative water source, landscape amenity) can mean there are competing objectives.

3.2.2. Impediments for the Uptake of WSUD and Post-Construction Issues

Interviews with WSUD practitioners found that the current policy framework for WSUD in South Australia was considered the major impediment for greater uptake. WSUD is referred to in almost all local development plans, but there is no mandatory requirement for developers to adopt WSUD principles in urban developments. Site reviews and interviews also revealed a lack of information on: the likely long term performance of WSUD features, operation and maintenance requirements, and expected cost-benefit ratio. This lack of information can impede local governments and developers in developing a strong business case for adoption of WSUD approaches. Local governments can also find it difficult to obtain the extra operational budget often required for the O & M of WSUD features compared to conventional approaches.

There was a perception that local governments have limited inter-departmental capacity for the implementation and management of WSUD approaches. WSUD is still relatively new so many practitioners in local government are still developing their capacity to design and implement WSUD features. For example, it was thought that a lack of knowledge on the suitability of filter media and plants for different locations and functions has impeded the successful implementation of WSUD systems.

Interviews with local government practitioners found there was a lack of understanding of the required maintenance tasks and costs for WSUD elements, which is influenced by the paucity of WSUD system monitoring and performance assessment. This can lead to a lack of maintenance for many small scale WSUD systems following installation. Some practitioners proposed the need for maintenance budgets for larger scale WSUD projects that are separate from general works operational budgets. Local government practitioners highlighted that there have been cases where local governments have inherited sub-optimal WSUD systems from developers that have caused problems with ongoing O & M.

The local government practitioners interviewed highlighted a need for capacity building across their industry and improved processes to involve the local community as key requirements to encourage greater WSUD uptake. Community awareness and engagement has been recognised as an important enabler for the implementation and long-term performance of WSUD features in academic literature [23]. This study found a number of other impediments and these were listed in the following common themes [17]:

- Consistent and coordinated application of WSUD in planning frameworks and development approvals processes.

- Need to further develop local government capacity for WSUD implementation.
- Enabling WSUD adoption through state-level targets and policy.
- Development of the knowledge-base for WSUD in the local context.
- Need for improved understanding of how small-scale distributed WSUD systems can address catchment-level objectives.

3.3. Community Consultation: Investigating the Social and Technical Impediments, Drivers and Opportunities for the Uptake and Management of WSUD Systems

The outcomes of community consultation regarding WSUD are summarised in Table 4. Although residents and other stakeholders are likely to have daily interaction with WSUD systems they usually have limited involvement in the planning and design of WSUD systems in their local area because this is generally conducted by local government or developers. In the case of Greenfield developments the scope for community consultation prior to implementation is limited, therefore it is important to understand the socio-technical drivers that influence community receptivity to the uptake of WSUD systems. The information generated through community consultation can help water professionals and managers to suitably design new developments for future residents [24].

Table 4. Details of focus group and interview outcomes.

Aspects/Site	Mawson Lakes	Lochiel Park	Springbank Waters	Christie Walk	Harbrow Grove	Mile End
Focus group participants (residents)	22	16	15	10	5	6
Interview participants (Key informants & residents)	Six environ-ment group, local magazine editor, teachers, business owner & real estate agent	Seven teacher, local government councilor & representatives of various community associations	Five community liaison officer & residents	Three site education convener & residents	Five residents	Three local business owner & two real estate agents. 23 short interviews with residents
Demographics of all participants	Median age 40–59 yet all age groups represented. 59% tertiary educated Mix of old & newer residents	Median age 60–74 Mostly home owners 90% tertiary educated Mostly new residents (<2 years)	Median age 40–59 yet all age groups represented. 40% tertiary educated Median residency 2–5 years Culturally diverse	Median age 60–74 80% home owners 90% tertiary educated Mix of old & newer residents	Median age 60–74 Mostly homeowners Mix of education Mostly old residents (>6 years) Culturally diverse	Median age 60–74 Mostly homeowners Mostly secondary education Mostly older residents >6 years
Knowledge of the WSUD system	Participants differed widely: higher amongst interview participants	Higher for key informants and long term residents	Few participants had a working knowledge of WSUD system	High: correct on main features & added minor features	Some knowledge of functional features but no understanding of system	Majority had no understanding of bio-retention systems

The following highlights some of the key findings from the interviews and focus groups from the six case study sites listed in Table 4:

- Residents at all the case study sites were found to be motivated to improve efficiency in the use of mains drinking water.
- Consistent with that ethic of saving, residents supported the expanded use of recycled water and rainwater (e.g., for use in the laundry and swimming pools), or retrofitting older suburbs with recycled water supply to households.
- Residents were generally aware of recycled water infrastructure, and the significance of 'purple pipes' in differentiating recycled water from drinking water supply systems. Also, residents perceived recycled water schemes as providing security against future water restrictions during droughts. This support existed even at the two retrofit sites where there was a lack of awareness of their local systems.

- Residents were not always able to articulate how alternative water systems such as ASR work, but in principle supported their application for reducing mains drinking water use.
- In sites where flooding had been a problem, e.g., Mile End, residents recognised the role of WSUD systems in flood control, with most residents indicating that the inclusion of WSUD systems has been effective in alleviating flood risk.
- The capacity of WSUD systems to improve quality of runoff was not well understood.
- In terms of understanding ecological processes, residents near wetlands seemed generally aware of the cleansing function of reed beds, but the design intent of landscaped swales was not clear for residents.
- The amenity benefits of WSUD features, such as greenscape, recreational areas, community gardens, biodiversity and waterways, was perceived as supporting healthy outdoor activity and the building of social capital within the community.
- Sites with active residents groups (Christie Walk, Lochiel Park and Mawson Lakes) had accessed information on WSUD from local government and had, when required, lobbied local governments, developers and the water utility for repairs and improvements.
- At Mile End, a site where there was a lack of awareness of their WSUD system, residents noted some drawbacks to WSUD features. For example, raingardens reduced on-street parking and there were seasonal variations in WSUD vegetation health and appearance.
- At all sites, residents reported operational problems with the WSUD systems. These included downpipes not connected to harvesting tanks, ponds not holding water, gross pollutant traps not functioning, incorrect vegetation, litter blocking drains, and lack of water clarity in water bodies.
- At Lochiel Park in particular, poor design and installation of WSUD systems had caused residents significant cost issues, frustration, and ill feeling towards the developer or local government. However, there was also recognition by these residents that much of the WSUD development was still experimental so not everything was going to work the first time.
- Those residents who were highly involved in the day to day management of WSUD features, or those who felt well informed and consulted, experienced a sense of pride in the green credentials of their development.

The need for community education on sustainable water use was a common point of agreement for further action across the sites. Addressing the lack of understanding and information about WSUD system operations through education was identified as a requirement to improve community receptivity to WSUD systems. More positively, Christie Walk and Lochiel Park residents expressed a belief that they could serve as exemplars for Adelaide to build community awareness and expertise about sustainable water management.

3.4. Understanding the Potential of WSUD for Flood Control, Demand Management and Runoff Volume Reduction

According to the *30 Year Plan for Greater Adelaide* [25] "the ratio of infill development to fringe development in metropolitan Adelaide will gradually shift from the current ratio of 50:50 until about 70% of all new housing is being built within existing urban areas". Infill development poses challenges to state and local governments with regard to the management of stormwater runoff. This is because increasing the density of existing urban catchments tends to increase impervious area. During storm events, this increased impervious area produces a greater volume of runoff, an increase in peak runoff flow rates and a reduction in the time to peak flow compared to the existing catchment prior to infill development [26].

Since existing stormwater management systems are designed for urban development with a lower impervious area than that which is likely to exist following infill development, increased flows may be beyond the capacity of the existing drainage system. This has implications for risk management because there may be a greater frequency of flood occurrence as existing stormwater management systems will not be able to cater for increased flows.

The following options may be considered to address the risk due to the infill developments:

- Do nothing: Accept the reduced capacity of the system to manage flooding at the desired frequency with no measures to overcome the problem.
- Enhance system capacity: Increase the capacity of the stormwater management system by construction of new drainage systems in addition to or replacing the existing pipe and channel network. Thus, upsizing or duplication of existing pipe and channel systems based on the new flow regime.
- Employ WSUD measures: Implement a program of progressive on-site flow management measures for new re-development sites (e.g., detention tanks, extended detention tanks, retention tanks, infiltration systems) to mitigate the impact of increased flow.

Some of the measures in the above last option are currently being implemented in South Australia and other Australian states. According to South Australian regulations in the Australian Building Code [27], it is currently mandatory for all new dwellings and some additions to include an alternative water supply to supplement the mains water supply system. In the absence of a recycled water supply, this is typically achieved by implementing a minimum one kilolitre rainwater tank. Some local governments have additional stormwater detention policies. These require a development to detain stormwater on site using storages in such a way that a specified volume of runoff is collected, stored and allowed to drain away through an orifice of specified size. These tanks are designed to capture the initial volume of runoff during a rainfall event to reduce the peak flow rate of stormwater runoff. This body of work is being conducted to assess the ability of WSUD based retention and detention mechanisms to extend the life of existing stormwater infrastructure.

3.4.1. Selection of Modelling Tool

To select a suitable modelling tool, a review of existing tools was conducted based on the hydraulic capability of the model, the ability of the model to assess WSUD tools and the ability of the model to process long time-series of continuous rainfall data. PC SWMM (CHI Software) was selected for continuous modelling of catchment runoff. This model was selected because it has been based on the widely available US EPA SWMM model which has been used in several studies employing continuous simulation of catchment runoff involving WSUD devices [28,29]. It also has useful features in addition to US EPA SWMM which allow the user to quickly and effectively assess model calibration, process long flow time-series and rapidly import data collected in a geographical information system environment.

3.4.2. Application of Modelling Tool and Modelling Steps

To examine the effect of WSUD to mitigate the effects of infill development on stormwater runoff, infill development scenarios (with and without WSUD) were applied to catchments representing existing residential development in Adelaide. In this paper, we describe the results for one site, the Frederick Street catchment in Glengowrie, South Australia, depicted in Figure 2. The Frederick Street catchment is approximately 45 hectares in size and contained 577 allotments during an initial study in 1992–1995. These were almost entirely residential.

The following steps were used in the hydrological analysis:

1. A hydrological model was constructed representing the runoff properties at the site.
2. The model was calibrated to existing flow data.
3. The model was run with 19 years of continuous rainfall data from a nearby rain gauge and the 1, 2, 5 and 10 year ARI peak flows for the current site conditions were determined using partial series analysis techniques [30–32]. The 5 Year ARI was assumed to represent the design flow capacity for the existing drainage system.
4. An identical model of the catchment was then produced representing the existing infill development scenario considered realistic based on current development trends.

5. Step 3 was then repeated for the post-infill development scenarios to determine the impact of infill development on the 5 Year ARI outflow.
6. To examine the impact of distributed WSUD solutions on runoff, a model identical to the redevelopment case in Step 4 was produced which included distributed retention and detention options throughout the catchment.

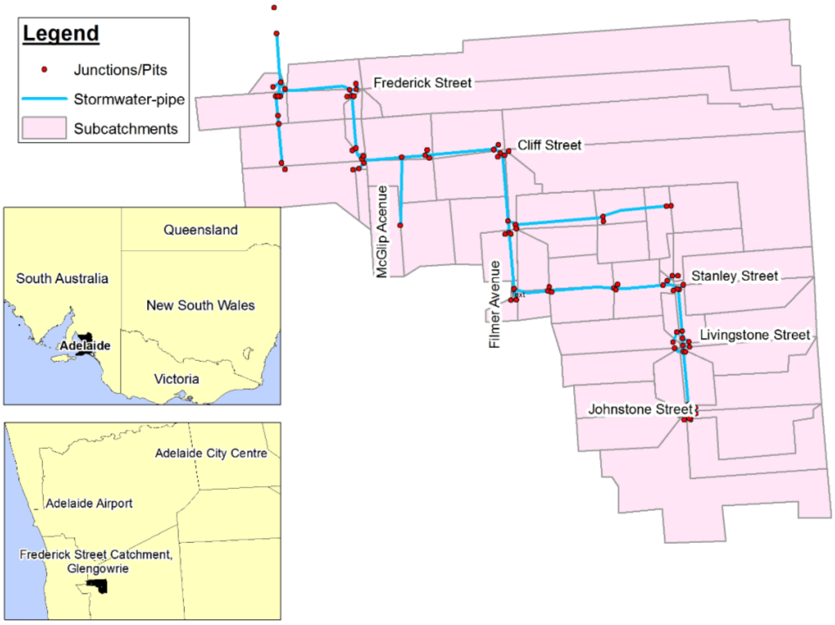

Figure 2. Location and outline of the Frederick Street catchment.

3.4.3. Modelling of Development Scenarios

Monitoring of runoff from the Frederick Street catchment was undertaken from 1992 to 1995. This was complemented by measuring the levels of directly connected impervious area (A_{DCI}) (the area of hard surfaces, such as roads and roofs, which are directly connected to the drainage system via other hard surfaces), indirectly connected impervious area (A_{ICI}) (the area of hard surfaces over which runoff flows over a pervious area prior to reaching the drainage system) and pervious area (A_P) (area through which water may infiltrate, such as vegetated areas and soil surfaces). The total catchment area was divided into 54 sub-catchments and the A_{DCI}, A_{ICI} and A_P of each sub-catchment was determined [33]. The overall percentage of A_{DCI}, A_{ICI} and A_P across the whole catchment in 1993 was 30.4%, 17.1% and 52.5%, respectively, and this was simulated as a base scenario (Scenario A). This base was then used to produce development scenarios as follows:

- Scenario A—The initial impervious area in 1993;
- Scenario B—The initial impervious area + 20%;
- Scenario C—The initial impervious area + 20% with 100 × 1 kL rainwater tanks;
- Scenario D—The initial impervious area + 20% with 100 × 5 kL rainwater tanks;
- Scenario E—The initial impervious area + 20% with 100 × 1 kL detention tanks;
- Scenario F—The initial impervious area + 20% with 100 × 5 kL detention tanks;
- Scenario G—The initial impervious area + 20% with 300 × 5 kL rainwater tanks;
- Scenario H—The initial impervious area + 20% with 300 × 5 kL detention tanks.

The progress of infill development was examined by increasing the A_{DCIA} by 20% at the expense of A_{ICIA} and A_{PA}. This increase was based on the development of approximately 200 new houses on existing blocks (where an existing house was demolished and 2 new houses were constructed in their place). The connected impervious area of these housing lots was based on the A_{DCIA}, A_{ICIA} and A_{PA} of new lots observed in the area since 1993 (where A_{DCIA} was approximately 70% based on an analysis of aerial photography).

The tank scenarios were based on having 100 or 300 tanks in the redeveloped catchment, which equates to approximately 12.8% or 38% of all homes. In each case, rainwater tank usage was assumed to be 100 L/day [34], and each rainwater tank was assumed to be connected to 200 m^2 of impervious surface (roof). Detention tanks were also assumed to be connected to 200 m^2 of roof, and each was fitted with a 20 mm outflow pipe.

3.4.4. Model Results and Analysis

The changes in the 1, 2 and 5 Year ARI peak flow rates and the volume retained by rainwater tanks are shown in Table 5.

Table 5. Changes in runoff peak flow and volume of runoff for the projected development scenarios.

Scenario	1 Year ARI (m^3/s)	2 Year ARI (m^3/s)	5 Year ARI (m^3/s)	10 Year ARI (m^3/s)	Volume Retained (ML/annum)
A	0.9	1.1	1.6	2.2	0
B	1.3	1.5	1.8	2.3	0
C	1.3	1.5	1.8	2.3	2.1
D	1.3	1.4	1.8	2.3	1.0
E	1.3	1.4	1.8	2.3	0
F	1.3	1.4	1.8	2.3	0
G	1.2	1.4	1.8	2.3	9.7
H	1.2	1.3	1.7	2.2	0

The results indicate that a 20% increase in impervious area due to infill development (Scenario B) increased the 2, 5 and 10 year ARI flow rates. The inclusion of 100 individual 1 kL rainwater tanks with infill development progress (Scenario C) showed limited potential to reduce the frequency of peak flows in the catchment. Note that the 1, 2, 5 and 10 Year ARI of the catchment containing the 1 kL rainwater tanks was very similar to Scenario B, without the tanks. The results indicated that increasing the size of rainwater tanks to 5 kL (Scenario D) also had little impact on the peak flow rates, indicating that rainwater tanks alone did not have a significant impact on managing flow peaks. When the number of 5 kL rainwater tanks was increased to 300 across the catchment (Scenario H), there was a greater, yet relatively small impact on runoff flow rates. This is most likely attributable to the relationship between rainwater tank usage and the availability of storage space at the beginning of rainfall which caused high runoff peak flows.

The implementation of 1 kL detention tanks instead of rainwater tanks (Scenario E) also produced little effect on runoff in the catchment, with results largely comparable to rainwater tanks. When the number of detention tanks was increased to 300, the greatest impact of all scenarios was obtained, however, it was still not able to reproduce the 1, 2, 5 and 10 year ARI flows of the pre-infill development (Scenario A). The contributing factor to the small reductions in peak flow was the limited capacity of the pipe drainage system, which was approximately equivalent to the 2 year ARI. Due to a relatively "flat" grade across the catchment, runoff in excess of the pipe capacity caused surface flooding to occur within the catchment. For this reason the tank storages had the effect of reducing the surface flooding before reducing the pipe flows. A further limitation may be attributed to the limited impervious area connected to the tanks (i.e., roof only).

These results are contrary to the findings of previous authors such as Vaes and Berlamont [35], who found that rainwater tanks had the potential to reduce the peak flow of storm events from a 5 Year ARI to 1 Year ARI in some cases. The Vaes and Berlamont study was based on very high estimates of tank storage volume per unit roof area (5 kL per 100 m^2 roof, with 30% of all impervious area connected to tanks) which was not considered to be a realistic assumption for the case study area in Adelaide. However, the results do agree with the findings of more recent studies investigating the retrofit of an urban catchment with rainwater tanks. Petrucci et al. [36] indicated that the installation of retention tanks in a small urban catchment could have influence over regular rainfall events, but were too small or too few to influence runoff flow rates from large rainfall events.

Further modelling and analysis using the developed methodology by Myers et al. [33] highlighted that a complete retrofit of every allotment in the catchment with retention or detention, or the construction of street scale rain gardens, was effective at maintaining peak flow rates at pre-infill development levels.

4. Conclusions

A methodology has been presented for undertaking an evidence-based process to evaluate the implementation of WSUD, its drivers and impediments to further implementation. The outcomes of the methodology demonstrated the benefits of a multifaceted approach that included social enquiry and stakeholder engagement, technical assessment of WSUD systems in the field and modelling studies. Key outcomes of the overall study included and inventory of WSUD sites in the study area, their drivers, impediments to further WSUD implementation, documentation of community perceptions of differing WSUD approaches, an investigation into the effectiveness of WSUD case studies and the potential of other potential WSUD approaches to provide water services.

The inventory of WSUD systems in South Australia demonstrated that the uptake of these systems has historically been focussed on stormwater management by local government. The inventory showed the most common WSUD approaches implemented in Adelaide were: wetlands, bioretention, managed aquifers and infiltration (swales). The vast majority of WSUD systems were retrofit projects predominantly built on existing public land and managed by local government.

Local water professionals reported the most common drivers for WSUD implementation were: stormwater flow reduction, improved runoff water quality and mains water conservation. Other drivers mentioned included reduction in servicing costs and the need for preservation of vegetation or to improve landscape amenity.

The investigation into the impediments for the increased uptake of WSUD systems in South Australia highlighted the need for a strong underlying policy which may encourage developers to adopt WSUD approaches. The difficulty in assessing the long term benefits and costs prevents councils from developing a strong business case for WSUD projects. Also local governments can find it difficult to obtain an O & M budget for these features. Water sector practitioners noted that major impediments to WSUD uptake included a lack of knowledge around WSUD maintenance requirements and a paucity of WSUD post-implementation monitoring and performance assessment. WSUD capacity building and greater community involvement were highlighted as ways to improve the implementation rate and quality of WSUD systems. The post implementation assessment of developments with WSUD features highlighted that the design intent of WSUD elements is often constrained by poor implementation.

The community consultation found that the water conservation and flood mitigation roles of WSUD were well recognised, however, the water quality improvement aspect was not well appreciated. The community also highlighted that the landscape amenity benefits of WSUD features can enable a more active, attractive and connected community. Some technical and implementation issues were highlighted during the consultation process. A key finding was the need for improved communication processes among the local community, developers and local government to ensure that the community are informed and educated. It was important that the community had the opportunity to provide feedback, based on their experiences, for the improved design, O & M of WSUD systems.

The investigation into the WSUD potential for flood mitigation indicated that rainwater tanks or detention tanks, when provided to 12.8% of the total homes make little change in the peak flows when compared to the pre infill development period. If these rainwater tanks and detention tanks were provided in 38% of these homes, only some peak flow reductions could be realised, but pre-infill development runoff peak flow and volume conditions were not restored.

We believe that water professionals and water managers around the world will be able to apply the methodology presented in this paper to understand the effectiveness of the WSUD approaches and the issues associated with their anticipated uptake by local governments, service providers and developers.

Acknowledgments: This study was funded by the Goyder Institute for Water Research in South Australia (http://goyderinstitute.org/).

Author Contributions: Ashok Sharma and David Pezzaniti planned the study and developed execution methodology; Baden Myers, Sattar Chavoshi and David Kemp planned and conducted stormwater modelling; Stephen Cook and Grace Tjandraatmadja and Priya Chacko executed the post implementation assessment and investigated gaps in WSUD implementation policies; Rosemary Leonard, Barbara Koth and Andrea Walton conducted community consultation. All the authors contributed in drafting the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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