Mains Water Neutral Gardening:
An integrated approach to water conservation in sustainable urban gardens

Joshua Joseph Byrne B.Sc. (Hons)

This thesis is presented for the degree of Doctor of Philosophy

School of Engineering and Information Technology

Murdoch University

2016

INTENTIONALLY BLANK PAGE

I declare that this thesis is my own account of my research and contains as its main content work which has not previously been submitted for a degree at any tertiary institution.

Joshua Joseph Byrne

July 2016

INTENTIONALLY BLANK PAGE

ABSTRACT

The role of urban green space in contributing to the liveability of cities and towns is well recognised. Residential gardens make up a large portion of urban green space and how they are designed and managed will determine whether they contribute to environmental enhancement and human wellbeing, or become additional sources of resource depletion and pollution. This thesis demonstrates ways in which gardening can contribute to urban sustainability through thoughtful design and the clever management of water. Two new concepts are presented to achieve this objective: ‘Sustainable Urban Gardening’ and ‘Mains Water Neutral Gardening’.

Sustainable Urban Gardening (SUG) is a multi-criteria sustainability framework that promotes a series of goals, including Energy Efficiency; Organic Waste Recycling and Soil Management; Biodiversity and Habitat Restoration; Organic Pest and Disease Management; Local Food Production; Water Conservation; and Health and Wellbeing of Householders.

Mains Water Neutral Gardening (MWNG) is a site-responsive, integrated approach to water system design and management in residential gardens. It incorporates available lot-scale alternative water sources, such as greywater, rainwater and groundwater, with efficient irrigation practices and local environmental conditions to establish holistic water budgets that are capable of meeting garden water requirements as part of a water-sensitive landscape design.

Three residential case study gardens based on the SUG and MWNG concepts were designed, built and documented as part of this research, whilst also featuring extensively in Australian television and print media. Monitoring demonstrated a reduction in household mains water consumption of between 42% and 92% when compared to local averages whilst addressing the intended SUG goals. The findings show the potential for greywater, rainwater and sustainably managed groundwater to contribute to mains water savings as part of a well-considered landscape design and household, however the high cost of supply in comparison to mains water (on a dollar per kilolitre basis) presents a barrier to broader adoption. Nonetheless, novel methods that optimise these water sources are demonstrated, enabling increased household resilience whilst reducing demand on constrained mains water supplies.

INTENTIONALLY BLANK PAGE

TABLE OF CONTENTS

ABSTRACT iii

TABLE OF CONTENTS iii

ACKNOWLEDGEMENTS xv

PREFACE xvii

PUBLICATIONS ARISING FROM THIS STUDY xix

CHAPTER 1: THESIS INTRODUCTION 1

1.1 CHAPTER INTRODUCTION 1

1.2 BACKGROUND TO STUDY 1

1.3 RESEARCH QUESTIONS 3

1.4 AIMS & OBJECTIVES OF THIS STUDY 3

1.5 THESIS STRUCTURE & SCOPE 4

CHAPTER 2: SUSTAINABLE GARDENING & WATER 7

2.1 CHAPTER INTRODUCTION 7

2.2 SUSTAINABLE URBAN GARDENING 7

2.3 WATER MANAGEMENT IN URBAN CENTRES 13

  2.3.1 TRADITIONAL APPROACHES 13

  2.3.2 EMERGING APPROACHES 14

2.4 LOT-SCALE WATER SYSTEMS: OPPORTUNITIES & CONSTRAINTS 16

  2.4.1 GREYWATER SYSTEMS 16

  2.4.2 RAINWATER HARVESTING 20

  2.4.3 RESIDENTIAL GROUNDWATER BORES 23

2.5 LANDSCAPE WATER CONSERVATION CONCEPTS & PRACTICES ... 24

2.6 SUMMARY OF KNOWLEDGE GAPS & LINKAGES TO RESEARCH QUESTIONS 26

CHAPTER 3: MAINS WATER NEUTRAL GARDENING 27

3.1 CHAPTER INTRODUCTION 27

3.2 MAINS WATER NEUTRAL GARDENING DEFINED 27

3.3 MAINS WATER NEUTRAL GARDENING METHODOLOGY 28
  3.3.1 ESTIMATING GARDEN WATER REQUIREMENT 28
  3.3.2 MEETING PLANT WATER DEMAND WITH GREYWATER 30
  3.3.3 RAINWATER YIELD 33
  3.3.4 GROUNDWATER EXTRACTION & RECHARGE 34
3.4 MODEL TESTING & VERIFICATION 36
CHAPTER 4: CASE STUDY 1 37
4.1 CHAPTER INTRODUCTION 37
4.2 CASE STUDY OVERVIEW 37
4.3 LANDSCAPE DESIGN 38
  4.3.1 DESIGN INTENT & PROJECT INSIGHTS 38
4.4 WATER SYSTEM INFRASTRUCTURE 50
  4.4.1 GREYWATER REUSE SYSTEM 50
  4.4.2 RAINWATER HARVESTING SYSTEM 50
  4.4.3 LANDSCAPE HYDROZONES & IRRIGATION SYSTEM 51
  4.4.4 WATER SYSTEM INTEGRATION 53
4.5 WATER BALANCE MODELLING 55
  4.5.1 GREYWATER VOLUMES 55
  4.5.2 IRRIGATION DEMAND 56
  4.5.3 RAINWATER VOLUMES 57
  4.5.4 MAINS WATER NEUTRAL BALANCE 58
4.6 MONITORING 59
  4.6.1 MONITORING SCOPE & PURPOSE 59
  4.6.2 MONITORING MATERIALS & METHOD 59
4.7 RESULTS & ANALYSIS 59
  4.7.1 HOUSEHOLD WATER USE BY SOURCE 59
  4.7.2 GREYWATER VOLUMES – ACTUAL VS MODELLING 61
  4.7.3 RAINWATER VOLUMES – ACTUAL VS MODELLING 62

4.7.4 IRRIGATION VOLUMES – ACTUAL VS MODELLING........................65

4.7.5 ENERGY INTENSITY OF WATER SOURCES..66

4.8 REFLECTIONS & LESSONS LEARNED..66

4.8.1 WATER SYSTEM EQUIPMENT PERFORMANCE.................................66

4.8.2 MONITORING METHODOLOGY & RELIABILITY OF DATA.............68

4.8.3 ALTERNATIVE WATER SYSTEM COSTS & PAYBACK PERIODS.....69

CHAPTER 5: CASE STUDY 2..73

5.1 CHAPTER INTRODUCTION..73

5.2 CASE STUDY OVERVIEW..73

5.3 LANDSCAPE DESIGN..74

5.3.1 DESIGN INTENT & PROJECT INSIGHTS..74

5.4 WATER SYSTEM INFRASTRUCTURE..84

5.4.1 GREYWATER REUSE SYSTEM..84

5.4.2 RAINWATER HARVESTING SYSTEM...84

5.4.3 LANDSCAPE HYDROZONES & IRRIGATION SYSTEM......................85

5.5 WATER BALANCE MODELLING...88

5.5.1 GREYWATER VOLUMES..88

5.5.2 IRRIGATION DEMAND..89

5.5.3 RAINWATER VOLUMES..90

5.5.4 MAINS WATER NEUTRAL BALANCE...91

5.6 MONITORING...92

5.6.1 MONITORING SCOPE & PURPOSE..92

5.6.2 MONITORING MATERIALS & METHOD..92

5.7 RESULTS & ANALYSIS..92

5.7.1 HOUSEHOLD WATER USE BY SOURCE...92

5.7.2 GREYWATER VOLUMES – ACTUAL VS MODELLING......................95

5.7.3 RAINWATER VOLUMES – ACTUAL VS MODELLING.......................95

5.7.4 IRRIGATION – ACTUAL VS MODELLING...97

5.8 REFLECTIONS & LESSONS LEARNED 98

5.8.1 WATER SYSTEM EQUIPMENT PERFORMANCE 98

5.8.2 MONITORING METHODOLOGY & RELIABILITY OF DATA............. 99

5.8.3 ALTERNATIVE WATER SYSTEM COSTS & PAYBACK PERIODS.... 99

CHAPTER 6: CASE STUDY 3.. 103

6.1 CHAPTER INTRODUCTION 103

6.2 CASE STUDY OVERVIEW.. 103

6.3 LANDSCAPE DESIGN 104

6.3.1 DESIGN INTENT & PROJECT INSIGHTS 104

6.4 WATER SYSTEM INFRASTRUCTURE 114

6.4.1 GREYWATER REUSE SYSTEM 114

6.4.2 RESIDENTIAL GROUNDWATER BORE... 114

6.4.3 RAINWATER HARVESTING SYSTEM 114

6.4.4 LANDSCAPE HYDROZONES & IRRIGATION SYSTEM.................... 115

6.5 WATER BALANCE MODELLING... 118

6.5.1 GREYWATER VOLUMES 118

6.5.2 GROUNDWATER RECHARGE & EXTRACTION 119

6.5.3 IRRIGATION DEMAND... 120

6.5.4 RAINWATER VOLUMES 121

6.6 MONITORING.. 122

6.6.1 MONITORING SCOPE & PURPOSE.. 122

6.6.2 MONITORING MATERIALS & METHOD.. 122

6.7 RESULTS & ANALYSIS 123

6.7.1 HOUSEHOLD WATER USE BY SOURCE 123

6.7.2 GREYWATER VOLUMES – ACTUAL VS MODELLING 125

6.7.3 GROUNDWATER VOLUMES – ACTUAL VS MODELLING............. 126

6.7.4 IRRIGATION – ACTUAL VS MODELLING 127

6.7.5 RAINWATER VOLUMES – ACTUAL VS MODELLING 127

6.7.6 ENERGY INTENSITY OF WATER SOURCES 129

6.8 REFLECTIONS & LESSONS LEARNED 131

6.8.1 WATER SYSTEM EQUIPMENT PERFORMANCE 131

6.8.2 MONITORING METHODOLOGY & RELIABILITY OF DATA...........132

6.8.3 ALTERNATE WATER SYSTEM COSTS & PAYBACK PERIODS......132

CHAPTER 7: DISCUSSION...136

7.1 CHAPTER INTRODUCTION...136

7.2 RESPONSE TO RESEARCH QUESTIONS...136

CHAPTER 8: CONCLUSION..144

8.1 CHAPTER INTRODUCTION...144

8.2 STUDY AIMS & OBJECTIVES ADDRESSED 144

8.3 CLOSING SUMMARY & OPPORTUNITIES FOR FURTHER WORK....146

REFERENCES...150

APPENDICES 170

APPENDIX 1: ABC *GARDENING AUSTRALIA* STORIES AIRED ON NATIONAL TELEVISION: 2006–2016 170

LIST OF TABLES

Table 1: Sustainable Urban Gardening framework sustainability goals, desired outcomes, design and operational considerations and supporting references. 10
Table 2: Modelling inputs for estimating garden water demand (adapted as noted). 29
Table 3: Summary of the sustainable landscape design elements and supporting gardening activities at case study 1 based on the Sustainable Urban Gardening framework. 40
Table 4: Regulatory greywater design volumes compared to estimated volumes for case study 1. 55
Table 5: Hydrozone irrigation demand modelling inputs for case study 1. 56
Table 6: Estimated irrigation demand by hydrozone for case study 1. 57
Table 7: Rainwater harvesting modelling inputs for case study 1. 57
Table 8: Rainwater harvesting modelling outputs for case study 1, using daily time-step, supply-demand side modelling. 58
Table 9: Mains Water Neutral Gardening water balance by tank size for case study 1. 58
Table 10: Garden and indoor non-potable water use volumes by source for case study 1. 63
Table 11: Greywater system costs for case study 1. 69
Table 12: Rainwater system costs for case study 1. 71
Table 13: Summary of the sustainable landscape design elements and supporting gardening activities for the case study 2. 75
Table 14: Regulatory greywater design volumes compared to estimated rates for the case study 2. 88
Table 15: Irrigation modelling inputs for case study 2. 89
Table 16: Estimated irrigation demand by hydrozone for case study 2. 90
Table 17: Rainwater harvesting modelling outputs for case study 2, using daily time-step, supply-demand side modelling. 90
Table 18: Rainwater harvesting modelling outputs for case study 2. 91
Table 19: Mains Water Neutral Gardening water balance by tank size for case study 2. 91
Table 20: Garden and indoor non-potable water use volumes by source for case study 2. 96
Table 21: Greywater system costs for case study 2. 100
Table 22: Rainwater system costs for case study 2. 101

Table 23: Summary of the sustainable landscape design elements and supporting gardening activities for case study 3. 105
Table 24: Regulatory greywater design volumes compared to estimated volumes for case study 3. 118
Table 25: Rainwater modelling input values for case study 3. 120
Table 26: Hydrozone irrigation demand modelling inputs for case study 3. 120
Table 27: Estimated irrigation demand by hydrozone for case study 3. 121
Table 28: Rainwater harvesting modelling outputs for case study 3, using daily time-step, supply-demand side modelling. 121
Table 29: Rainwater harvesting modelling outputs for case study 3. 122
Table 30: Greywater system costs for case study 3. 133
Table 31: Groundwater bore system costs for case study 3. 134
Table 32: Rainwater system costs for case study 3. 135
Table 33: Impact of greywater in reducing mains water demand for each case study site. 137
Table 34: Contribution of rainwater to garden water demand and other purposes for case studies 1 and 2. 138
Table 35: Rainwater yield for each case study sites for various storage sizing scenarios. 139
Table 36: Garden areas by hydrozone for each case study site. 140
Table 37: Contribution of greywater, rainwater and groundwater to mains water savings. 140
Table 38: Volume of mains water used against size of property and irrigated areas for each case study site. 141

LIST OF FIGURES

Figure 1: Sustainable Urban Gardening framework goals. 8

Figure 2: Water demand of medium and high-water-use plants across the year against the greywater application rate from a three-bedroom house with two, three and four occupants (location of Perth, Western Australia). 31

Figure 3: Water demand of medium and high-water-use plants across the year against the greywater application rate from a three-bedroom house with improved water efficiency with two, three and four occupants (location of Perth, Western Australia). 32

Figure 4: Cumulative supplementary irrigation requirements for a three-bedroom house (improved water efficiency) with two, three and four occupants (location of Perth, Western Australia). 33

Figure 5: Mains Water Neutral Gardening concept schematic showing water flows in and out of a residential lot-scale system. 35

Figure 6: Landscape plan for case study 1. 42

Figure 7: Photographs of case study site. 43

Figure 8: Hydrozone plan for case study 1. 52

Figure 9: Water system design schematic illustrating the integration of the various water sources at case study 1, including water flows from source to sink. 54

Figure 10: Estimated application rates compared with estimated hydrozone water demand (location of Perth, Western Australia). 56

Figure 11: Water use by source for case study 1. 60

Figure 12: Modelled versus actual greywater volumes generated at the case study 1 expressed as an irrigation application rate (location of Perth, Western Australia). 62

Figure 13: Comparison of rainfall during study period (2010–2011) and recent average (1996–2010) for case study 1 (using data from Bureau of Meteorology Station 009215). 64

Figure 14: Comparison of modelled irrigation demand versus actual usage for case study 1. 65

Figure 15: Landscape plan for case study site 2. 77

Figure 16: Photographs of case study site 2. 78

Figure 17: Hydrozone plan for the case study 2. 86

Figure 18: Water system design schematic illustrating the integration of the various water sources at the case study 2, including water flows from source to sink.........................87
Figure 19: Estimated greywater application rates compared with estimated hydrozone water demand for case study 2 (location of Perth, Western Australia)..........................89
Figure 20: Water use by source at case study 2. 93
Figure 21: Modelled versus actual greywater volumes generated at the case study 2 expressed as an irrigation application rate (location of Perth, Western Australia). 95
Figure 22: Comparison of rainfall during study period (2012) and recent average (1996–2010) for case study 2 (using data from Bureau of Meteorology Station 009215).........96
Figure 23: Comparison of modelled irrigation demand vs actual usage for CS2. 97
Figure 24: Landscape plan for case study site 3. 107
Figure 25: Photographs of case study site 3..108
Figure 26: Hydrozone plan for case study 3. 116
Figure 27: Water system design schematic illustrating the integration of the various water sources at the case study 3, including water flows from source to sink.......................117
Figure 28: Estimated greywater application rates compared with estimated hydrozone water demand for case study 3 (location of Perth, Western Australia).......................119
Figure 29: Water use by source for case study 3. 124
Figure 30: Modelled versus actual greywater volumes generated at the case study 3 expressed as an irrigation application rate (location of Perth, Western Australia). 125
Figure 31: Groundwater extraction and assumed recharge volumes (shown as an average over the year) for case study 3. 126
Figure 32: Comparison of modelled irrigation demand versus actual usage. 127
Figure 33: Rainwater versus mains water use for internal demands by month at CS3. 128
Figure 34: Comparison of rainfall during the study period (2015) and recent average (1996–2010) at case study 3 (using data from Bureau of Meteorology Station 009215). 129
Figure 35: Energy intensity of each of the water sources at case study 3, compared with the IWSS and seawater desalination. 130
Figure 36: Proportion of household electricity used to supply water from on-site sources at case study 3. 131

LIST OF ABBREVIATIONS

AARF – Average Annual Rainfall (mm)

APS – Area of Permeable Surfaces (m^2)

Ar – Area (m^2)

ARD – Average Root Depth (m)

BAU – Business as Usual

CF – Crop Factor (factor of 1)

CS – Case Study

D – Demand (L/day)

ER – Evaporation Rate (mm/day)

ERC – Effective Roof Catchment (m^2)

GDD – Greywater Diversion Device

GDWE – Groundwater Extraction (L)

GDWI – Groundwater Infiltration (L)

GDWIF – Groundwater Infiltration Factor (%)

GndW – Groundwater

GW – Greywater

GWA – Greywater Applied (L)

GWR – Garden Water Requirement (L/day)

Hz – Hydrozone

HzWD – Hydrozone Water Demand (L/day)

IEf – Irrigation System Efficiency Factor (%)

IUWM – Integrated Urban Water Management

IWSS – Integrated Water Scheme Supply

LIR – Loading Infiltration Rate (mm/day)

MW – Mains Water

MWBV – Mains Water Backup Valve

MWNG – Mains Water Neutral Gardening

MWOD – Mains Water Outside Demand (L)

PWD – Plant Water Demand (mm/day)

RA – Roof Area (m^2)

Rf – Rainfall (mm)

RW – Rainwater

RWID – Rainwater Inside Demand (L)

RWOD – Rainwater Outside Demand (L)

RWT – Rainwater Tank

RWY – Rainwater Yield (L/day)

SMHC – Soil Moisture Holding Capacity (mm/m)

SUG – Sustainable Urban Gardening

SWR – Soil Water Reservoir (mm/m)

TO – Tank Overflow (L)

WF – Watering Frequency (days)

WSUD – Water Sensitive Urban Design

WUR – Water Use Rate (mm/day)

ACKNOWLEDGEMENTS

To my supervisors, Professor Goen Ho, Professor Peter Newman and Dr Martin Anda, thank you for your patience and continued support over the years. I consider myself extremely fortunate to have had such experienced and committed research supervision and I look forward to our continued collaboration. I would also like to acknowledge the guidance and mentoring provided by Dr Kuruvilla Mathew who started me on my PhD journey and made me promise to finish it regardless of what other life opportunities came my way. I also acknowledge my parents John and Rosslyn, and brother Tobias, who provided support and encouragement in their own ways throughout my candidature and early career.

The case studies in this thesis had a very practical focus, involving the development of three gardens, the first two of which were at rental houses. I am grateful to the owners for providing me with the opportunity to test my ideas at their properties and for supporting my endeavours. I established strong working relationships with a number of tradespeople during this process, from plumbers to builders to instrumentation technicians, and their generous sharing of time and skills is greatly appreciated. I would like to make particular mention of Ben Alpers and John Warmt-Murray, who were involved in all three case study projects. Your humour, responsiveness and creativity are acknowledged.

I would also like to thank Ashwin Nayak, Jamie Stephens and John Hunt for their research support, as well Luke Priddle and Tessa Bradbury for their assistance rendering my landscape designs and schematic drawings into quality graphics.

Lastly, I want to thank my wife Dr Kellie Maher, who despite completing her PhD in three and a half years flat, understood my need to play the long game in order to properly test my ideas and harvest the fruits of my labour. Thank you for your patience, love and support; and here’s to spending more time in our garden together.

INTENTIONALLY BLANK PAGE

PREFACE

Gardening has always been more than a hobby for me. It’s been a practical way to reduce my environmental footprint by utilising the space around me to grow food, recycle wastes and create habitat for other life. It was my interest in gardening that led me to study environmental science to further my understanding of the natural world and our role in it. I gardened throughout my studies, both as a source of income and, more fundamentally, as part of my daily life.

In 2001, as a university student in my mid-twenties, I experienced water restrictions for the first time. Sprinkler bans had been introduced to reduce the amount of water being used in Perth gardens, which at the time was accounting for nearly 60% of residential demand. Perth was growing, rainfall was declining and sprinkler irrigation was limited to twice per week. Anyone who has gardened in Perth would know that it is not possible to successfully grow food in our sandy soils in summer on this regime, so it meant hours of hand watering, or breaking the rules and risking a fine. The system that I had always known to provide ample water from the tap was no longer coping.

My honours research, which I undertook around this time, provided me with an opportunity to explore new developments in landscape irrigation technology for water conservation, but it was clear that technical advances were only part of the solution. A hard shift to xeriscaping (low-water-use landscaping) had limitations too, especially in Perth’s Mediterranean climate where shady, irrigated gardens provide important respite from harsh summer conditions. And what about growing food? This is a water-intensive activity, particularly in summer, but delivers multiple benefits, including improved nutrition, wellbeing and food security.

Utilisation of alternative water resources seemed logical, but there was little happening locally in this space at that time. Although greywater reuse had recently been legalised in Western Australia and government rebates were introduced for a period to encourage its uptake, along with rainwater tanks and garden bores, adoption was relatively low and industry capacity was poor.

Rain had failed on the east coast too. By midway through the first half of the first decade of this century, water restrictions were in place in cities and towns throughout southern and eastern Australia. This period would become known as the millennium drought, and water conservation dominated the gardening industry. The drought finally broke in the east, but rainfall continued to decline in Perth and the southwest.

With this as a backdrop, I began an immersive and methodical journey of designing, building and monitoring a series of gardens that are presented as case studies in this thesis. This allowed me to explore the opportunities and limitations of lot-scale alternative water systems, plus establish an original framework for ‘sustainable urban gardens’ in an attempt to balance the conflicting goals of water conservation and gardening. In addition to documenting this process for my research, I showcased the step-by-step development of each of the gardens on national television through my role as a presenter on the Australian Broadcasting Corporation’s (ABC) *Gardening Australia* program. Between 2006 and 2016, over 100 stories were aired on these case study projects, attracting an audience of around 600,000 people per episode, plus dozens of feature magazine articles and two books. Each of the gardens was opened to the public and attracted over 8,000 visitors combined. I mention this to demonstrate the extent of the influence this research has already had via the popular media, in addition to this thesis and the academic publications arising from it.

PUBLICATIONS ARISING FROM THIS STUDY

Books

Byrne, J., 2007. *The Green Gardener*, Camberwell, Victoria, Penguin.

Byrne, J., 2013. *Small Space Organics*, Camberwell, Victoria, Hardie Grant.

Journal Papers

Byrne, J.*, Dallas, S., Nayak A., & Anda M. Quantifying the benefits of residential greywater reuse – three case studies from Perth, Western Australia. In review for *Water Science and Technology*.

*80% contribution, including drafting the paper and incorporating feedback from co-authors.

Refereed Conference Papers

Byrne J.*, Hunt, J., Anda, M. & Ho, G., 2008. Meeting plant water demands with greywater. *Proceedings of the AWA Onsite and Decentralised Sewerage Conference*, 12–15 October 2008, Benalla, Australia.

*80% contribution, including drafting the paper and incorporating feedback from co-authors.

Byrne, J.*, Dallas, S. & Newman, P., 2014. Optimising residential water efficiency: the Josh's House Project, *Proceedings of the Australian Water Association OzWater Conference*, 29 April – 1 May 2014, Brisbane.

*50% contribution of written content.

Coombes, P. J., Smit, M., Byrne, J.* & Walsh, C. Water resources, stormwater and waterway benefits of water conservation measures for Australian capital cities. *Proceedings of the Stormwater 2016 National Conference*, 29 August – 2 September 2016, Gold Coast, Australia.

*20% contribution of written content.

Coombes, P. J., Smit, M., Byrne, J.* & Walsh, C. Stormwater, waterway and water resources benefits of water conservation measures in Australian cities. *Proceedings of the 56th New Zealand Hydrological Society and 37th International Hydrology and Water Resources Symposium*, 28 November – 2 December 2016, Queenstown, New Zealand.

*20% contribution of written content.

Technical Reports

Byrne, J., 2012. *Integrated Water Systems for Sustainable Urban Landscapes*. Project No. NY09024, Horticulture Australia Limited, Sydney.

Josh Byrne and Associates (JBA)*, 2013. *Residential Grey-water Plumbing Guidelines*, JBA, Fremantle.
*20% contribution of written content.

Industry Papers

Josh Byrne and Associates (JBA)*, 2016. *Green Space Alliance Discussion Paper*. Prepared for the Green Space Alliance, Perth, WA.
*20% contribution of written content.

Television Stories

Byrne, J., 2006–2016. 117 stories featured on Australian Broadcast Corporation's *Gardening Australia* program, covering the implementation and management of the case study sites during the study period. (Refer to Appendix 1 for story titles and links).

CHAPTER 1: THESIS INTRODUCTION

1.1 CHAPTER INTRODUCTION

This chapter begins by providing a brief background to the study by highlighting the importance of urban greenspace in a highly urbanised world, and how we must find creative solutions to enhance it despite the increasing challenges of constrained space and limited water (Section 1.2).

The research questions are presented in Section 1.3, supported by the aims and objectives of the study in Section 1.4. Finally, Section 1.5 provides an overview of the thesis structure and scope.

1.2 BACKGROUND TO STUDY

Cities are the major habitat of most humans now. At the same time as the dramatic shift has happened – from 5% urban in the early 1900s to over 50% urban in the 2000s – there has been increasing awareness that human impact on the planet has exceeded its capacity to absorb the growing tonnes of waste or to provide the necessary resources (Rees, 1992; Newman & Kenworthy, 1999; Newman *et al*., 2009). Perhaps, more basically, the human adaptation to concrete, steel and glass has not met human biophilic needs (Wilson, 1984; Beatley, 2012). Many approaches are needed to reduce human ecological footprint whilst improving liveability (Newman, 2006). This thesis seeks to find ways that gardening can contribute to urban sustainability through thoughtful design and the clever management of water.

The term ‘sustainability’ is now well and truly established in contemporary landscape design vernacular (Mendel, 2012; Johnson, 2015). In the context of this thesis, the term ‘sustainable urban gardens’ refers to an approach that considers a range of environmental and human need considerations such as, energy efficiency, nutrient recycling, biodiversity, local food production, health and wellbeing, and of course water conservation. These factors can also be viewed as sustainability ‘goals’ that can help shape a particular landscape design response. Importantly, these goals need to be addressed with an integrated approach, as outlined later in this thesis, as by simply focusing on one element a garden may inadvertently lead to a negative impact. The singular aim to reduce garden water use is a good example.

Water conservation became a major priority in Australia within the gardening industry and broader community following the drought conditions that were experienced across much of the southern and south-eastern Australia during the first decade of this century (Bureau of Meteorology, 2015). Some initial responses to water shortages were positive, such as promoting the use of low-water-use plants, especially native species that also provide biodiversity benefits, or the advancement of efficient irrigation systems which minimised water wastage. However, a number of trends were not so positive, resulting in knock-on effects that may not have been initially considered. For example, the extensive use of paving and other hard surfaces to replace areas that were previously irrigated, or the substitution of lawn with synthetic turf, had other impacts. In both cases these responses may have led to a reduction in water use, but can also contribute to increased localised heating, increased stormwater run-off, as well as the use of materials with high embodied energy and an overall greater source of environmental impact.

In the haste to promote low-water-use gardens, the landscaping and urban development industries often promoted designs as being ‘sustainable’ because they used less water, without consideration of these downstream impacts. What this also meant was that gardening activities that do require water, such as food gardens, are more likely to be excluded despite the fact they have a role to play in creating ‘sustainable’ urban living environments. Growing vegetables is a comparatively high-water-use gardening activity but it has significant health, social and environmental benefits through providing low-cost nutritious food with a low carbon footprint because it is consumed near to where it is grown.

A holistic and sophisticated approach to how we design and manage our gardens is required if these spaces are going to genuinely contribute to improving the liveability and overall sustainability of urban environments in the face of a growing urban population and drying climate. Perth in Western Australia represents a highly relevant location to undertake this study, with dramatically declining rainfall (Bureau of Meteorology, 2015), projected increase in heatwave conditions (Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology, 2015), and an expected doubling of mains water demand over the next 40 years (Department of Water, 2014), despite current water sources being highly constrained (Water Corporation, 2015). In addition, Perth is undergoing rapid densification (as with many cities around the world), resulting in reduction of private greenspace from infill residential development (Grose, 2009), meaning we need to be highly creative and resourceful to realise the many benefits that greenspace can provide from smaller spaces.

This thesis builds on the many disciplines and trades that are part of the house building and home gardening industries. Given the critical importance of water in supporting urban landscapes, and human populations more generally, specific emphasis is placed on ways in which sustainable gardens can be established and maintained within the constraints of local water resources and limited space.

1.3 RESEARCH QUESTIONS

The research questions underpinning this thesis are as follows:

1. What constitutes a ‘sustainable urban garden’?
2. What are the opportunities for alternative water sources at the lot-scale to support sustainable urban gardens and reduce reliance on mains water? Specifically:
    a. Is lot-scale greywater reuse an effective way to reduce mains water use in sustainable urban gardens?
    b. Does lot-scale rainwater harvesting have a role to play in reducing the reliance on mains water for meeting the water demand of sustainable urban gardens in summer-dry climates?
    c. What role do residential groundwater bores (where this is supplementary to a town scheme supply) play in reducing mains water demand when used in conjunction with greywater and rainwater systems in sustainable urban gardens?
    d. What are the mains water savings from integrating a suite of alternative water sources, along with efficient irrigation practices, as part of a water-sensitive landscape design approach to sustainable urban gardens?
3. What is the significance of such an approach and what are the wider applications and barriers to adoption?

1.4 AIMS & OBJECTIVES OF THIS STUDY

The aims and objectives of this study in support of the research questions identified above are as follows:

1. Establish a conceptual framework for ‘sustainable urban gardens’ as the basis for informing a landscape design and determining a responsive landscape water budget.

2. Identify the role, opportunities and constraints of mains water, greywater, rainwater and groundwater in supporting sustainable urban gardens.
3. Develop an integrated water system model for sustainable urban gardens to meet landscape water demand and reduce reliance on mains water.
4. Test the robustness of the model through the monitoring and analysis of sustainable urban garden case study sites.

1.5 THESIS STRUCTURE & SCOPE

This chapter (Introduction) provides a general background and context to the study, as well as identifying the aims of the thesis and establishing the key research questions to be addressed.

Chapter 2 is a literature review on sustainable gardening and water management in urban centres, and is divided into six sections. Section 2.2 discusses the notion of ‘Sustainable Urban Gardening’ and a working definition is derived through the identification of key urban gardening sustainability goals, desired outcomes, and design and operational considerations. This is intended to inform the landscape design process as the basis for determining a realistic landscape water budget commensurate with this type of design intent. Section 2.3 reviews traditional and emerging approaches to water management in urban centres. Section 2.4 focuses on the opportunities and constraints surrounding residential lot-scale alternative water sources, including greywater, rainwater and groundwater. Section 2.5 covers key landscape water conservation concepts and practices. Section 2.6 summarises the key findings of the literature review and identifies the knowledge gaps to be addressed in this thesis.

Chapter 3 introduces a novel residential water demand model termed ‘Mains Water Neutral Gardening’ (MWNG) as an original contribution. The model establishes a property (house and garden) water budget at the beginning of the landscape design process in order to effectively integrate available alternative water sources to meet landscape water demand and offset mains water use.

Chapters 4, 5 and 6 present three case studies which are based on the MWNG model. Each case study chapter provides a project overview, description of the specific landscape and water system design components, and a summary of the property’s MWNG water balance modelling. The monitoring methodology is outlined and the results and analysis of actual water consumption are presented.

Chapter 7 (Discussion) provides a synthesis of the results of the three case studies in order to address the original research questions. The MWNG principles are evaluated and suggestions made on how relevant technical, regulatory and economic barriers can be addressed for improved water conservation in sustainable urban gardens.

Chapter 8 (Conclusion) concludes the thesis by summarising how the aims and objectives of the study have been addressed, and what further work could be done to progress the concepts presented and discussed.

Supporting materials are provided in Appendices 1 and 2 and are referred to in the body of the thesis accordingly.

INTENTIONALLY BLANK PAGE

CHAPTER 2: SUSTAINABLE GARDENING & WATER

2.1 CHAPTER INTRODUCTION

This chapter is divided into six sections that are aligned with the research questions and objections of this thesis as listed in the previous chapter. Section 2.2 explores the notion of ‘Sustainable Urban Gardening’ which is presented as a multi-criteria framework developed by the author as part of this study and published in popular literature (Byrne, 2007 and 2013). Its purpose here is to establish an understanding of the types of functions and activities expected of a sustainable garden so as to inform a landscape design and determine an appropriate landscape water budget.

Section 2.3 reviews urban water supply issues, providing insights into the challenges that exist with large-scale centralised approaches to water service delivery in meeting growing demands and changing needs. The emergence of new approaches to urban water management that promote local utilisation of alternative fit-for-purpose water sources for meeting landscape water demand is explored.

Section 2.4 focuses on residential lot-scale alternative water sources, including greywater, rainwater and groundwater. Technical limitations and opportunities for better integration and system performance are identified for further discussion and testing in subsequent chapters. Section 2.5 covers key landscape water conservation concepts and practices for improved garden water use efficiency. Section 2.6 summarises the key findings from the literature and identifies the knowledge gaps to be addressed in this thesis.

2.2 SUSTAINABLE URBAN GARDENING

As the world’s population continues to urbanise, the role of urban greenspace in contributing to people’s quality of life and how it can support the metabolism of cities is gaining increased attention (Newman *et al.*, 2009; Beatley & Newman, 2009; Newman & Jennings, 2008; Hall, 2010). The term metabolism considers the resource inputs and waste outputs of settlements through a biological systems approach, and it provides a framework for achieving reduced resources and wastes while improving liveability for cities (Newman, 1999). Significant research has been undertaken on topics such as the role of vegetation in mitigating the urban heat island effect (Newman & Matan, 2013) and the integration of greenspaces with the urban water cycle (Revell & Anda, 2014), as well as the importance of greenspace for human health and wellbeing more broadly (Beatley, 2013).

Residential gardens, which can be defined as private areas surrounding domestic dwellings (Cameron *et al*., 2012; Gaston *et al*., 2005), make up a large portion of the metropolitan landscape in low-density suburban cities around the world (Loram *et al*., 2007; Mathieu *et al*., 2007) and these spaces have the potential to make a significant positive contribution to the sustainability of urban environments or, conversely, to be additional sources of resource depletion and pollution (Beatley & Newman, 2013). Despite the significant spatial contribution of residential gardens towards urban greenspace, a review of the literature reveals a paucity of academic attention in the area of the sustainability of residential gardens and their relative impact to eco-system services (Cameron *et al*., 2012). Studies by Gross & Lane (2007) and Gaston *et al*. (2005) however demonstrated a strong participatory interest in sustainable (or ecological) gardening and there is a large and growing body of technical and popular literature in this field.

Byrne (2007; 2013) presents an integrated framework (Figure 1) for Sustainable Urban Gardening (SUG) based on desired outcomes and services that are recognised as contributing to improved urban sustainability. These can also be seen as 'sustainability goals' and include Energy Efficiency; Organic Waste Recycling and Soil Management; Biodiversity and Habitat Restoration; Organic Pest and Disease Management; Food Production; Water Conservation; and Health and Wellbeing of Householders.

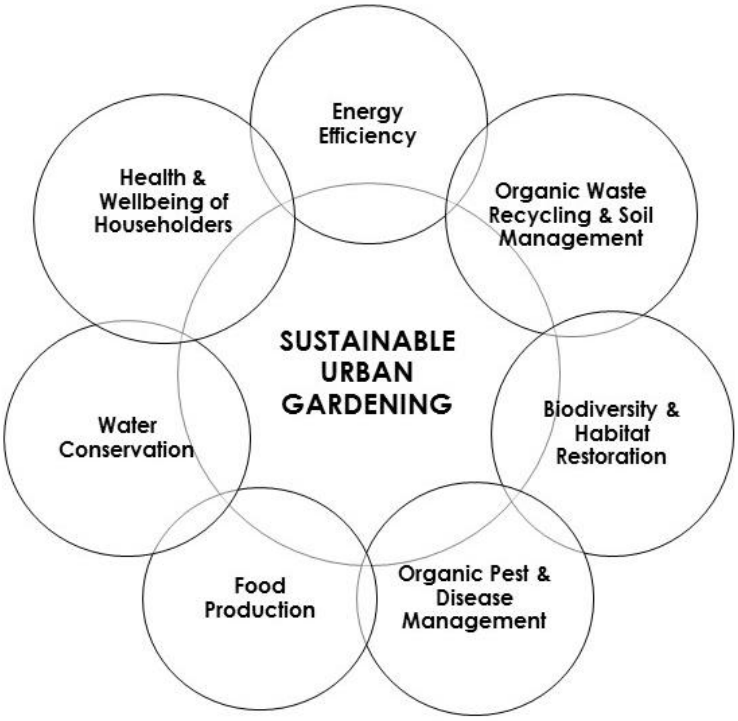


Figure 1: Sustainable Urban Gardening framework goals (source: adapted from Byrne, 2007 and 2013).

Underpinning the desired outcomes for each of the goals is a series of design and operational considerations that need to be addressed in order for the goal to be achieved. For example, the desired outcome for the Energy Efficiency goal is a reduction in fossil fuel use from both the embedded and operational energy inputs of the garden. The design and operational considerations proposed to achieve this include: the use of low carbon, repurposed and recycled materials in construction; the use of trees and vines for controlled seasonal shading and solar gain to enhance the thermal performance of the home; maximising water pumping efficiency for irrigation needs; promoting household food production and on-site organic waste management to reduce transport mileage; and the avoidance of fossil fuel based fertilisers and fossil fuel dependent equipment for maintenance.

Table 1 lists the desired outcomes and design and operational considerations for each of the seven sustainability goals of the SUG framework. References from the international literature are provided alongside the desired outcomes, indicating how the framework relates to globally significant responses to sustainable development. A list of leading local practical and technical references has also been provided against the relevant design and operational considerations for context.

There are obvious conflicts and synergies between the different goals in the model. The outcomes of each are likely to mean that the required procedures of others need to be modified. For example, there are limits to how much food can be produced before using the entire space of a garden for this purpose and thus reducing biodiversity and habitat restoration outcomes. There are water use implications with these choices too, given the relatively high water requirements of growing of vegetables and fruits compared to that of say endemic plant species (Connellan, 2013) which would feature heavily in a habitat garden (Grant, 2003).

The SUG model provides a framework to assist with the identification of opportunities or limitations in relationship to these goals and the prioritisation of strategies to address these. The focus of this research relates directly to goal number six of the model being Water Conservation and innovative approaches to water management for sustainable gardening at the residential lot-scale more broadly. Accordingly, the following sections of this chapter focus on the identification of leading urban water management approaches, knowledge gaps, and opportunities for further work to progress this field.

Table 1: Sustainable Urban Gardening framework sustainability goals, desired outcomes, design and operational considerations and supporting references.

SUSTAINABILITY GOAL 1: ENERGY EFFICIENCY		
Desired Outcomes	**Design & Operational Considerations**	**Leading Practice References**
Reduced fossil fuel use from embedded energy in materials and in the operations of the house and garden. Grübler & Nebojša (1996) Keoleian *et al.* (2000) Chow *et al.* (2003) Swart *et al.* (2003) Xing *et al.* (2011)	Use low carbon or repurposed/recycled materials used in garden structures.	Cross & Spencer (2008)
	Select and position plantings to enhance thermal performance of dwelling and local microclimate.	Hollo (2005)
	Consider energy efficiency when pumping water.	Sharma *et al.* (2015)
	Incorporate local food production and organic waste management for reduced transport.	Marshall (2003)
	Avoid use of non-renewable materials (including synthetic fertilisers) and fossil fuel dependent machinery for maintenance.	Mollison (1988)
SUSTAINABILITY GOAL 2: ORGANIC WASTE RECYCLING & SOIL MANAGEMENT		
Desired Outcomes	**Design & Operational Considerations**	**Leading Practice References**
Local soil carbon regeneration and nutrient recycling. Reeves (1997) Deelstra & Girardet (2000) Lal (2004)	Create compost, mulch and other soil conditioners from on-site organic wastes.	Marshall (2003)
	Practice crop rotation and utilise legumes for nitrogen fixing.	Bennet (2006)
	Use natural mineral and organic fertilisers.	Bennet (2006)
	Understand and manage pH.	Handreck & Black (2010)
	Use appropriate detergents and personal care products if applying greywater to garden.	Byrne (2013)

SUSTAINABILITY GOAL 3: BIODIVERSITY & HABITAT RESTORATION

Desired Outcomes	**Design & Operational Considerations**	**Leading Practice References**
Enabling indigenous plant, insect and animal life to thrive. Kim (1993) McKinney (2002) Breuste (2004) Gaston *et al.* (2005)	Plant native species suitable for attracting insects and birds.	Grant (2003)
	Create different habitats with layered plantings and water features.	Grant (2003)
	Make 'hiding places' for wildlife through landscaping features.	Grant (2003)
	Manage cats and dogs (predation and harassment).	Grant (2003)

SUSTAINABILITY GOAL 4: ORGANIC PEST & WEED MANAGEMENT

Desired Outcomes	**Design & Operational Considerations**	**Leading Practice References**
Achieving natural ecosystem functioning that controls pests and weeds without toxic chemical use. Margni *et al.* (2002) Tilman *et al.* (2002) Shrewsbury and Leather (2012)	Understand the nature of pests and weeds and design for ecological and cultural control.	Crawford (2015) McMaugh (2000)
	Implement physical and mechanical techniques of weed control.	French (1997)
	Implement physical and natural techniques for pest control.	French (2002) Crawford (2015) McMaugh (2000)

SUSTAINABILITY GOAL 5: FOOD PRODUCTION

Desired Outcomes	**Design & Operational Considerations**	**Leading Practice References**
Producing household food supply supplementation. Nolan *et al.* (2006) Galluzzi *et al.* (2010) Zezza and Tasciotti (2010)	Create systems for intensive vegetable growing such as container gardening and rotating bed systems.	Byrne (2007)
	Plan what to plant based on climate, stagger plantings and combine short-, medium-, long-term crops and 'continual picking' varieties.	Byrne (2013)
	Collect seeds, especially non-hybrid heirloom species.	Fanton (1993)
	Incorporate herbs with multiple values (e.g. culinary, medicinal, insect deterrent, etc.).	Byrne (2013)

	Incorporate fruit trees and design to strategically maximise light and shade to understorey.	Glowinski (1997) Mollison (1992)
	Incorporate chickens, rabbits, other useful small animal species and plan pens (fixed or mobile) for integrated use.	Mollison (1988) Reading (1990)
SUSTAINABILITY GOAL 6: WATER CONSERVATION		
Desired Outcomes	**Design & Operational Considerations**	**Leading Practice References**
Reducing water-based ecological footprint. Wallace (2000) Hilaire *et al.* (2008) Khan *et al.* (2009)	Create suitable microclimate through wind breaks and shading.	Western Australian Water Resources Council (1986)
	Hydrozone to group plants with similar water needs and choose plants to fit water regime.	Sturman *et al*. (2004)
	Improve moisture retention of soil and mulch during hot-dry periods.	Handreck & Black (1991)
	Use efficient irrigation, including high performance drip emitters (where suitable) with accurate seasonal operation.	Connellan (2013)
	Collect rainwater for household and garden use (where appropriate).	NWC (2008a)
	Recycle greywater (where appropriate).	NWC (2008b)
	Utilise other locally available fit-for-purpose sources such as stormwater, groundwater or recycled water as appropriate.	Sharma *et al*. (2013)
SUSTAINABILITY GOAL 7: HEALTH & WELLBEING OF HOUSEHOLDERS		
Desired Outcomes	**Design & Operational Considerations**	**Leading Practice References**
Achieving a liveable housing habitat including daily contact with nature. Newman & Jennings (2008) Beatley & Newman (2009) Newman *et al*. (2009)	Create a safe and secure place for householders with sufficient space for eating, resting and recreation.	Mendel (2012)
	Ensure that natural features of garden are part of daily life.	Johnson (2014)

2.3 WATER MANAGEMENT IN URBAN CENTRES

2.3.1 TRADITIONAL APPROACHES

Around the world, traditional urban water management relies on large, centralised infrastructure (Sitzenfrei *et al.*, 2013). In most modern cities, water services are delivered via linear networks of buried pipes that connect customers to treatment works and, ultimately, to sources of water and sinks for wastewater (Marlow *et al*., 2013). This ‘big pipes in and big pipes out’ (Newman, 1993) or ‘take, make, waste’ (Daigger, 2009) approach typifies the low-density suburban expansion around modern, industrial cities and the adherence to a ‘Big Water’ (Sofoulis, 2005) approach by governments and utilities where a two-pipe model dominates, i.e. drinking water quality in and wastewater out via the sewer.

Whilst centralised water services have dramatically improved the hygiene of urban areas (Harremoës, 1997; Ma *et al.*, 2015), there is growing awareness regarding inherent lack of flexibility and adaptability (Daigger, 2009; Ma *et al*., 2015; Raucher and Tchobanoglous, 2014). This has been highlighted as a major shortcoming when planning for future needs (Larsen, 2011; Daigger, 2009), given the increasing interest in wastewater and stormwater as valuable resources to meet growing water demand (Barton & Argue, 2009; Daigger & Crawford, 2007).

Perth, with a population in excess of 1.7 million people (Australian Bureau of Statistics, 2011), has taken a centralised approach to water service delivery (Bettini *et al*., 2015), like many modern cities around the world, and it presents an interesting example of the inherent vulnerabilities at this scale. A growing population (Australian Bureau of Statistics, 2013) coupled with long-term decline in rainfall (Bureau of Meteorology, 2015) has seen a shift away from surface water reservoirs in Perth to increased dependency on groundwater extraction and, more recently, significant reliance on large-scale seawater desalination, which now accounts for around 50% of Perth’s Integrated Water Supply Scheme (IWSS) (Water Corporation, 2015). After an intensive deep sewerage program roll-out, the majority of the Perth metropolitan area is now serviced by one of four large-scale sewerage treatment plants from which over 80% of all sewerage is discharged into the ocean (Water Corporation, 2009). The energy cost of water is currently around 1.8kWh/kL across all sources supplying the IWSS, and 4.1kWh/kL for the seawater desalination component (Water Corporation, 2009), making Perth mains water the most energy intensive scheme of all capital cities in Australia (Bureau of Meteorology, 2015). The energy cost for sewerage pumping and treatment is estimated to be around 0.8kWh/kL (Water Corporation, 2015). Currently, the proportion of renewable energy used to offset this is estimated at less than 50%. With a total energy usage of around 131GWh, this equates to an annual greenhouse gas emissions contribution of 115kT per year in pumping and treatment alone (Water Corporation, 2015).

Approximately 70% of all water supplied by the Perth IWSS is consumed by residential customers, at an average of 106kL/person/year (Water Corporation, 2010), which is the highest per capita water use of all southern Australian capital cities (Water Corporation, 2009), and double that of many European and Asian cities. Around 40% of that supply is used for domestic irrigation, despite a high penetration of residential groundwater bore ownership and watering restrictions limiting garden irrigation with mains water to two days per week that have been in place since 2001 (Water Corporation, 2009). A further 16% is used for flushing toilets and filling washing machines (Water Corporation, 2010). In fact, of the 291GL of potable water supplied through the Perth IWSS, only around 50% is used for potable purposes (Water Corporation, 2010).

The use of water restrictions to limit household water despite record levels of capital expenditure is a highly visible sign of the system’s inability to cope with demand. Since 2010 these restrictions have been extended to include a complete ban on irrigating with mains water during winter months (June to August) and are now considered permanent water saving measures (Department of Water, 2015). Despite these, and other demand management strategies deployed over the past ten years, forecasted demand is expected to exceed supply by 120GL by 2030 (Water Corporation, 2009). Given the relatively high proportion of mains water that is used for gardens, it is conceivable that further watering restrictions could be introduced to prioritise in-house uses, in line with the types of total sprinkler bans seen previously elsewhere in Australia (Bureau of Meteorology, 2015). Further reductions will arguably have a significant impact on garden performance and subsequently have a detrimental impact on the liveability of Perth suburbs and wellbeing of residents.

2.3.2 EMERGING APPROACHES

To meet current and future challenges, such as climate change, and changes in population and land use, it can be argued that water infrastructure needs to become more flexible, adaptable and sustainable (Ho & Anda, 2006; Brown *et al.*, 2009; Domènech & Sauri, 2010). A number of transition theories have been developed to show how modern cities can adapt and become more water efficient and water sensitive. To this end, Integrated Urban Water Management (IUWM) (Marsalek *et al*., 2001; Vlachos & Braga, 2001; Mitchell, 2004; Hunt *et al*., 2005; Mathew *et al*., 2005) and Water Sensitive Urban Design (WSUD) (Wong & Brown, 2009; Sharma *et al.,* 2016) have emerged as alternative approaches to traditional centralised water system engineering.

IUWM and WSUD represent a shift towards an integrated approach to urban water systems which: (1) considers all parts of the system, (2) emphasises water conservation and alternative, fit-for-purpose water supplies, (3) is functional at a range of centralised and decentralised scales, and (4) incorporates connections with other environmental cycles (such as energy and nutrients) (Mitchell, 2004; Brown *et al.*, 2009; Hughes *et al*., 2006; Dallas *et al*., 2007; Bach *et al*., 2014).

These various fit-for-purpose applications and scales may include the following, depending on local sources and needs:

- Rainwater harvesting for direct fit-for-purpose uses with localised storage at household and cluster scales (Ho *et al*., 2008; Hunt *et al*., 2011a; Coombes *et al.*, 2003; Gurung *et al., 2012*; Umapathi *et al.*,2012).

- Stormwater harvesting to aquifer recharge and groundwater recovery and reuse at household, cluster and precinct scales (Hunt *et al*., 2005; Dillon *et al.*, 2014; Page *et al*., 2015).

- Groundwater extraction and treatment to fit-for-purpose uses for various drinking and non-drinking purposes at household, cluster and precinct scales (Lieb *et al.*, 2006; Hunt *et al*., 2008; Dhakal *et al*., 2015).

- Greywater collection, treatment to fit-for-purpose and reuse at household, cluster and precinct scales (Nolde, 2000; Priest *et al*., 2004; Friedler & Hadari, 2006; Ghisi & de Oliveria, 2007; Evans *et al*., 2008; Evans *et al*., 2009; Mohamed *et al*., 2013).

- Wastewater collection and treatment for reuse at household, precinct and district scales (Ho *et al*., 2001; Gardner, 2003; Radcliffe, 2006; Kunz *et al*., 2016).

Thus, the above alternative sources and uses show how the predominant two-pipe model can be adapted into a three-pipe model by means of dual reticulation for supply of an alternative water source for non-potable uses at various scales. Such schemes are not necessarily intended to lead to self-sufficiency, but rather to reduce the strain on surrounding centralised infrastructure (Smith *et al.*, 2005), or deliver other benefits, such as reduced energy intensity of water (Umapathi *et al.*, 2013; Gurung & Sharma, 2014), enhance environmental values (McFarlane *et al.*, 2009), reduced stormwater volumes and improved stormwater run-off quality (Burns *et al*., 2015), along with greater resilience of supply for non-drinking water purposes such as irrigation (Sharma *et al*., 2010).

The scale of alternative supply schemes (i.e. lot, cluster, precinct, or district) will depend on a range of factors, including the stage of development (i.e. new greenfield site compared with an established suburb with existing housing stock). Typically cost, logistics and general business case become more attractive when certain thresholds are met, however each application is likely to have its own unique drivers that influence scale and technology choice (Diaper *et al*., 2007).

The following section reviews residential lot-scale greywater, rainwater and groundwater in further detail as examples of alternative water sources, and the opportunities and constraints for their utilisation in meeting landscape water demands are discussed. It is important to note that whilst it may often be appropriate to supersede these lot-scale approaches with cluster or precinct schemes as flagged above, they present an immediate opportunity to reduce per capita mains water demand (Gray, 2002) and they have the potential to provide added security of supply for gardening.

2.4 LOT-SCALE WATER SYSTEMS: OPPORTUNITIES & CONSTRAINTS

2.4.1 GREYWATER SYSTEMS

Greywater is the component of domestic wastewater that excludes toilet waste (black water). Typically, it includes shower/bath, laundry and basin water. Kitchen (sink and dishwasher) drainage is also considered greywater but is usually excluded from most reuse systems due to the high content of food waste, grease and other contaminants requiring a higher level of treatment (Department of Health, 2010). Discussion is limited to greywater reuse here, rather than complete domestic on-site wastewater recycling, because in Australia, as within most modern metropolitan areas around the world, connection to sewer for the disposal of black water is typically mandatory (Crites & Tchobanoglous, 1998).

In Australia, the average person produces around 100L of useable greywater per day (Standards Australia, 2012) which, if effectively reused, could displace mains water for non-potable uses. For a four-person house, this equates to a potential greywater yield of 2,800L per week, or 145,600L per year if it can be properly utilised, and while the volumes of residential water consumption may vary widely around the world, the proportion of greywater still presents a considerable portion of the household water balance (Metcalf and Eddy, 1991).

At its most basic level, greywater can be collected in buckets and used for hand watering plants, or house drainage plumbing can be modified to enable water to be distributed to the garden rather than to sewer (National Water Commission, 2008b). At a more advanced level, greywater reuse apparatuses can be installed that range from simple greywater diversion devices (GDD) to enable more efficient garden watering, through to more sophisticated greywater treatment systems that process the greywater to a level suitable for higher level uses such as flushing toilets and washing clothes (National Water Commission, 2008b). Costs for such systems vary widely, ranging from a few hundred dollars for basic GDDs to above $10,000 for advanced GTDs (Wiltshire, 2005).

Internationally the requirements for approved greywater reuse varies widely, ranging from non-existent to prohibitive (Gross *et al.*, 2015). In Australia, the regulatory requirements for greywater reuse are governed at the state level, with approval for system installation and operation typically carried out at the municipal level, and whilst requirements do vary from state to state, the key considerations and local guidelines are based on well-developed technical standards and specifications including *AS/NZS 1547 On-site Domestic Wastewater Management* (Standards Australia, 2012); *AS/NZS 3500 Plumbing and Drainage – Water Services* (Standards Australia, 2003); *ATS 5200 Technical Specification for Plumbing and Drainage Products – Procedures for Certification of Plumbing and Drainage Products* (Australian Building Codes Board, 2013); *ATS 5200:460 Technical Specification for Plumbing and Drainage Products – Greywater Diversion Device* (American National Standards Institute, 2005); *HB 326 – 2008, Urban Greywater Installation Handbook for Single Households* (Standards Australia, 2008); and the *Residential Greywater Ready Plumbing Guidelines* (Josh Byrne and Associates, 2013).

In Western Australia, requirements for residential greywater reuse are set out in the *Code of Practice for the Reuse of Greywater in Western Australia* by the Department of Health

(2010). Sizing of a GDD irrigation area is a key part of system design approval and the process is explained here as it relates to the ability for GDDs to meet plant water demand, i.e. whether or not the volume of greywater distributed over a given area is adequate to sustain the water requirements of garden plantings (Byrne *et al*., 2008).

Sizing irrigation areas and surge tanks (which may be used to temporarily intercept flow) are based on estimated household greywater generation volumes, which are calculated by multiplying average greywater figures per individual (based on AS1547:2000) by the number of bedrooms in the house (assuming two people in the first bedroom and one person in each additional bedroom). The second factor in determining the size of a greywater irrigation area is the capability of the soil to receive the estimated greywater flows, known as the Loading Infiltration Rate (LIR). In Perth, a maximum allowable application rate of 10mm per day is normally applied based on free draining sands that are typical of the Swan Coastal Plain (Department of Health, 2010). The result is that if homes are under-occupied, or if the householders use less water than anticipated, then greywater volumes and therefore irrigation availability are likely to be inadequate.

A review of household occupancy figures published by the Australian Bureau of Statistics (2006) indicates that the majority of three and four bedroom homes in Perth, which together make up 95% of the separate housing stock where there are two or more occupants, are in fact under-occupied. It also stands to reason that the greywater volumes generated on a per person basis are likely to be in decline in keeping with the increased uptake of water-efficient fixtures and appliances as the result of changes in consumer trends and increased water efficiency requirements prescribed in the *National Construction Code of Australia* (Australian Building Codes Board, 2015). These reductions are reflected in reduced per capita water use figures across a number of cities, but have not been picked up in the evolution of the *Code of Practice for the Reuse of Greywater in Western Australia* from its inception in 2000 to the current version (Department of Health, 2010). In fact, the estimated greywater volumes increased from 93L per person per day in 2000, to 100L per person per day in 2005, and this remains unchanged in the 2010 version, noting that these figures assume a top-loading washing machine and no water-saving devices in the bathroom and laundry. The reduction in daily greywater volumes are potentially significant, if one considers a simple working example based on a 49% reduction in laundry greywater achieved by replacing top-loading washing machines with front loaders (Patterson, 2004), and a 35% reduction in bathroom greywater by installing water-efficient shower and tap fixtures (from 14L to 9L per minute and 9L to 6L per minute respectively) (Byrne *et al*., 2008).

The impact that greywater reuse can make in reducing household water consumption is not straightforward, especially from the use of GDDs for garden watering, largely due to a lack of real world data. Despite greywater reuse being the subject of significant research, the focus has mainly been on treatment and issues of risk mitigation (Gross *et al.*, 2005; 2006; 2007; 2008; Travis *et al.*, 2010; Maimon *et al*., 2014). There is a specific lack of available literature relating to GDDs and, in particular, their role in contributing to garden water demands and quantified mains water savings. Major reviews on greywater treatment technologies such as the ones by Li *et al*. (2009) and Ghunmi *et al*. (2011) which outline physical, chemical and biological treatment technologies and by Ghaitidak & Yadav (2013) and Gross *et al*. (2015), which explore 22 and 33 different technologies respectively, have no mention of GDDs. Other reviews by Pidou *et al*. (2007) and Gross *et al*. (2008), which review 64 and seven technologies respectively, and by Maheshwari & Pinto (2015) and Toifl *et al*., (2015) recognise GDDs but do not elaborate on their value in contributing to mains water savings. Diaper *et al*. (2004) noted that most innovation is taking place in the more complex treatment systems and this is evidenced by the fact that all of the aforementioned reviews have emphasised the more advanced physical, biological, and chemical technologies. The lack of academic inquiry into GDDs is also evidenced by well-published literature on other aspects of greywater reuse such as reuse for toilet flushing (Nolde, 2000; Friedler & Hadari, 2006; Ghisi & de Oliveria, 2007; Ghisi & Ferreria, 2007; Mourad *et al*., 2011) and its impact on municipal wastewater flows (Friedler *et al*., 2012; Penn *et al*., 2013).

A study undertaken in Victoria (Alternative Technology Association, 2005) reviewed the operation of six different greywater systems, including four GDDs, with mains water savings ranging from 0% to 33%. The transferability of these savings is limited however due to the variation in system type and application. Of interest is that the findings highlighted issues with disparity between greywater volumes and garden water needs. This was also identified in a local study by Evans *et al*. (2009) to assess the potential for GDDs to contribute to mains water savings across nine Perth household case study sites. Savings of between 9% to 37% were observed, with the most significant factor being whether the irrigation system and landscape design was in balance with the volume of greywater generated. In both cases, little information on the landscape water requirements or overall garden design were provided, so it is difficult to ascertain the actual impact of the systems or how they could be optimised.

Both the Alternative Technology Association (2005) and Evans (2009) studies highlight a number of barriers to the uptake of greywater, which included lack of technical understanding of how the systems operated, perceived complexity of regulatory requirements, high cost of systems (which can vary significantly depending on type of system and extent of plumbing works required), and difficulty in accessing quality information. Similar issues were identified by Ng (2004), in addition to the logistics of access to greywater plumbing in existing housing stock, all of which help to account for the relatively low uptake of greywater reuse for irrigation of less than 3% of households in Perth and 7.3% nationally across all capital cities, although this also includes recycled water generally (Australian Bureau of Statistics, 2013).

The poor uptake of greywater systems in Perth is also evident in the low number of rebates claimed as part of the aforementioned rebate scheme intended to promote their uptake (Marsden Jacob Associates, 2009). A report commissioned by the Water Corporation (Marsden Jacob Associates, 2009) to assess the impact of the rebate scheme on household water consumption indicated an increase in overall household water use across the properties that had installed a greywater system. As the nature of the study did not involve any further investigation, other than pre and post installation, it is difficult to ascertain the reason for this counterintuitive outcome. Possible scenarios could be that the greywater system installations were done as part of a broader landscape upgrade, which resulted in other areas using mains water. Another possibility is householders being dissatisfied with garden performance (due to greywater volumes not meeting plant water demand) and therefore increasing indoor water use to provide adequate water to the garden.

2.4.2 RAINWATER HARVESTING

The benefits of collecting rainwater for storage and later use are well documented, including reduced demand on mains water supply (Chong *et al.*, 2011), reduced stormwater flows into receiving drainage infrastructure (Burns *et al.*, 2015), and the potential for delivery of fit-for-purpose water with reduced energy intensity when compared to centralised water supply (Vieira *et al.*, 2015).

Rainwater is typically considered most suitable for non-potable indoor uses (such as toilet flushing and clothes washing) as well as garden irrigation (National Water Commission, 2008b), however its application is commonly extended to being connected to hot water services as well as supplying potable water demands, provided appropriate water quality protection measures are taken (National Water Commission, 2008b).

Like greywater reuse, the legalities surrounding rainwater harvesting in urban environments vary widely around the world, with the implications for population health and impact on surrounding water supply and stormwater infrastructure cited as the leading influences on restrictive use. In Australia, rainwater use can be governed by both state and local government regulation depending on location. In recent years there has been considerable uptake in the use of domestic rainwater tanks to augment household water supply during periods of drought, leading to requirements in some states and regions for the mandatory inclusion of rainwater tanks as part of new house building applications, plus the availability of rebates to assist with the cost of installation. The requirements for system design and installation are governed by national plumbing codes and technical guidelines, including *AS/NZS 3500 Plumbing and Drainage – Water Services* (Standards Australia, 2003)*, ATS 5200 Technical Specification for Plumbing and Drainage Products – Procedures for Certification of Plumbing and Drainage Products* (Australian Building Codes Board, 2013) and the *Rainwater Tank Design and Installation Handbook* (National Water Commission, 2008a).

While numerous studies have been published on various aspects of rainwater harvesting – such as rainwater quality implications for end uses (Sharma *et al*., 2015), the contribution to mains water savings and its role in attenuating stormwater flows (Coombes & Kuczera, 2003; Umapathi *et al.*, 2012), the energy intensity of supply (Umapathi *et al*., 2013; Gurung & Sharma, 2014; Tjandraatmadja *et al.*, 2015; Vieira *et al.*, 2015), and the costs of system installation and operation (Coombes *et al*., 2003; Gurung *et al*., 2012) – there are varying opinions on how best to optimise the use of rainwater in various climates (i.e. whether it is best used inside the home or outside, or a combination of both throughout the year).

Established industry modelling tools such as Aquacycle (Mitchell, 2001) or PURRS (Coombes & Kuczera, 2001) can inform suitable roof catchment areas and tank sizes to optimise system performance based on estimated demands. There are a number of open source online supply–demand side modelling tools also, as well as customised spreadsheet models tailored to specific regions such as Hunt *et al.* (2011b).

Determining the appropriate end use is particularly relevant in low rainfall or Mediterranean (winter-wet, summer-dry) climates, where it stands to reason that a lack of rain, combined with high summer irrigation requirements, would suggest rainwater is not viable for irrigation purposes. This may partially account for the comparatively low uptake of rainwater usage in WA (12.1%), compared to other Australian states such as NSW (19.3%), Victoria (29.5%) and Queensland (33.9%). Interestingly, South Australia defies this trend: despite its summer-dry climate, it has the highest use of rainwater as a source of water at 45.5% (Australia Bureau of Statistics, 2013).

Research by Loux *et al.* (2012) in Davis, California, which experiences a similar Mediterranean-type climate to Perth, examined the role of both rainwater and greywater in meeting landscape irrigation and toilet flushing demands across a range of building types, including a single residential family dwelling, which is the typology of interest here. It was identified that whilst rainfall is likely to be adequate to meet toilet demand during the limited seasonal rainy period, it was an impractical proposition for garden watering, given the inverse relationship between rainfall and landscape water demand. A combination of rainwater and greywater met both demands for part of the year only (winter, early spring and late autumn), noting that relatively modest storage volumes of 3750L (combined) were included, based on a 150m^2 roof catchment and approximately 100m^2 of landscaping. The major barrier for this approach was cost, due to the treatment requirements for the extended storage of the greywater and its use for internal purpose. Notably, the need for carefully considered landscaping with quantified understanding of landscape water requirements was presented, however the purpose and functionality from a sustainability perspective was not articulated.

Locally, Gray (2002) assessed the comparative impact of rainwater harvesting and greywater reuse on mains water consumption between the highly seasonal Mediterranean climate of Perth (728mm per year) compared with the more frequent rainfall patterns experienced in Brisbane (1,025mm per year) and Canberra (583mm per year). The impact of the greater number of days between rain events in Perth (5.7 days), compared with Brisbane (4.8 days) and Canberra (3.9 days), combined with the number of events with greater than 30 days between rain (19, 5 and 2 respectively) have a clear impact on rainwater yields and favour the use of greywater for meeting demands due to its availability year round. In this exercise, treatment systems were again assumed to enable the greywater to be used internally for toilet flushing and washing machine use to achieve the greatest reduction in mains water.

Whilst both these studies are highly relevant from a climate-type perspective, and demonstrate favourable mains water savings outcomes, details on how they can be better optimised through system integration are limited. Information on landscaping type and function is also absent.

2.4.3 RESIDENTIAL GROUNDWATER BORES

Groundwater that exists in fractured rocks and porous substrates presents another opportunity for substitution of mains water for garden irrigation provided it is of suitable quality and it can be demonstrated that its extraction can be sustained and does not adversely impact the surrounding environment (Smith *et al.*, 2005).

The availability and nature of groundwater resources varies enormously and its suitability for use based on water quality and quantity will be location specific (Harrington & Cook, 2014). Perth, for example, is unique among Australian capital cities with regards to local groundwater availability, and there are estimated to be over 167,000 residential groundwater bores used for garden irrigation (Department of Water, 2011). This equates to about 22% of all Perth homes (Australian Bureau of Statistics, 2009), with an average extraction rate of 440kL of water a year, totalling approximately 73GL or about 15% of all groundwater taken in the region (Department of Water, 2011). The next highest is Sydney with approximately 11,000 residential groundwater bores in total, followed by Melbourne with 8,000 and then Brisbane with 3,400 (Australian Bureau of Statistics, 2009).

In Western Australia, the Department of Water and Water Corporation promote the use of residential groundwater bores for garden irrigation as a means of reducing pressure on constrained mains water supplies (Department of Water, 2011; Water Corporation 2013), however over-extraction in the face of a drying climate (Bates *et al.*, 2008) is increasingly recognised as a threat to groundwater-dependent ecosystems, such as wetlands and springs (McFarlane *et al.*, 2012; Barron, 2014), plus it increases the risk of saltwater intrusion in areas near the coast and estuary (Department of Water, 2011; McFarlane, 2015).

The process for monitoring the sustainability of groundwater extraction is inherently complex given the complex set of variables, including changing rainfall, run-off and usage patterns (McFarlane *et al.*, 2012), and there is no standardised method across Australia (Harrington & Cook, 2014).

In Western Australia, the Perth Regional Aquifer Modelling System, or PRAMS (Department of Water, 2009), was jointly developed by the Department of Water and the

Water Corporation to assist with groundwater management and it provides useful guidance for understanding local infiltration rates as the basis for informing sustainable extraction volumes. It uses groundwater recharge coefficients previously developed by Prince (1997) for different land uses and surface treatments. For urban residential areas, it is estimated that 80–90% of rainfall falling on roofs and 60–70% of rainfall on the paved areas will infiltrate to groundwater. For lawns and gardens, net rainfall recharge rate is estimated as 30–40% of annual rainfall, resulting in a rainfall recharge rate in the range of 45–55% (Prince, 1997).

To some extent, falling groundwater levels resulting from reduced rainfall is being offset by increasing dwelling density resulting from urban infill, where smaller lot sizes (Urban Development Institute of Australia, 2015), with greater roof to lot ratios and reduced garden areas, results in higher stormwater infiltration.

In Perth, residential groundwater bores drawing from the superficial aquifer are not required to be licenced (Department of Water, 2011), although their usage is restricted to three times per week, with a complete ban in winter months, with the exception of essential maintenance (Department of Water, 2011). Notably, not all areas in the Perth area are suited to the use of bores, including areas where groundwater is salty, the ground is low-yielding, groundwater contamination exists, or previous overuse has led to impact on local wetlands or saltwater intrusion (McFarlane, 2015). Such areas are mapped and available from the Department of Water (2011).

2.5 LANDSCAPE WATER CONSERVATION CONCEPTS & PRACTICES

Residential gardens and public amenity landscapes are a major user of water in urban environments, especially in environments where rainfall is low or highly seasonal, and this is compounded in low density cities where gardens can make up a significant portion of the urban landscape.

In recent years there have been significant advances in landscape irrigation technology (Keller & Bliesner, 2014) in relation to the efficiency of emitters (drippers and sprinklers) as well as sophistication of controllers for automation. Considerable work has also been undertaken on the continued development of sensors and other devices that can help to reduce unnecessary watering (Byrne *et al*., 2002; Romero *et al.*, 2012; e Silva *et al.*, 2014). Technical guidelines for the hydraulic design of irrigation systems, component selection and installation, plus system scheduling (run time and frequency) are now well established in various industry standards and benchmarks (Costello *et al*., 2000; Cape, 2006; Irrigation Australia, 2012; Irrigation Association & American Society of Irrigation Consultants, 2014).

It is important to note, however, that landscape water conservation extends beyond the efficient application of water. Fundamental considerations have to be factored in at the design stage to ensure appropriate allocation of water resources. The ‘hydrozone’ model (Thayer & Asler, 1984) presents the basis for this. In its original sense, it relates to the allocation of water and energy resources relative to the intensity, or priority of use and visual importance. The concept can be expanded to consider a spatial relationship, where the highest resource requiring zones are kept small and intensive, and the lower use zones can be more extensive (Mollison, 1992).

In its simplest form, it involves grouping plants together based on their common water needs to allow for efficient servicing of irrigation without over (or under) watering particular crop types. This concept can be extended so as to take into account groups of similar plantings that are subject to different site conditions which affect microclimate and impact water use, such as aspect or rain shadow, as well as separating plantings based on their compatibility to water streams with specific water quality characteristics, such as the alkalinity of greywater (Byrne *et al*., 2008; Gross *et al.,* 2008). Appropriate dimensioning of hydrozones should also be given consideration so that they can be effectively and accurately serviced within the hydraulic constraints of the water supply (Sturman *et al*., 2004) and spatial properties of the selected emitter type, otherwise the ability to apply water effectively is significantly compromised, as is the ability to accurately estimate usage.

Significant information also exists on horticultural practices conducive to maximising water use efficiency (Western Australian Water Resources Council, 1986; Handreck & Black, 2010; Byrne, 2013). Creation of suitable microclimates to reduce evapo-transpiration losses, conditioning soil to improve moisture holding capacity and protecting exposed soil with appropriate mulch are all important, but alone will only result in partial reductions in mains water consumption when compared to the incorporation of alternative water sources.

2.6 SUMMARY OF KNOWLEDGE GAPS & LINKAGES TO RESEARCH QUESTIONS

This chapter has identified the important role that residential gardens can play in creating sustainable urban environments and provided a framework by which sustainable gardens can be described. In many parts of the world, including Perth in Western Australia, the amount of water required to support gardens is substantial, often placing strain on traditional ‘Big Water’ infrastructure. The introduction of demand management strategies, such as watering restrictions alone do not appear capable of resolving water security issues, and are in fact likely to limit broader sustainability outcomes which can be achieved at a local level through gardening as outlined in the SUG model (Table 1).

WSUD and IUWM promote a systems-based approach that facilitates greater opportunity for closing the loop on urban water processes and this thinking can be applied on a range of scales. The residential lot-scale is a relatively easy step, with opportunities for greywater reuse, rainwater harvesting and groundwater extraction being readily available now. The benefits are immediately apparent to the household and, if properly planned, are likely to yield community benefits when scaled up.

Despite the significant work undertaken to date with the development of alternative lot-scale water technologies for garden use, the advances presented appear relatively siloed, and from a gardening perspective, the story is incomplete. The optimal water-efficient garden requires the integration of a range of disciplines, trades and practices, such as landscape design, water systems engineering (including plumbing and irrigation) and horticulture. The better the overlap between these disciplines, the greater the likelihood of improved garden performance and greater water use efficiency. The following chapters are dedicated to closing this knowledge gap by addressing the research questions set out in Chapter 1.

CHAPTER 3: MAINS WATER NEUTRAL GARDENING

3.1 CHAPTER INTRODUCTION

This chapter presents a novel water use concept called Mains Water Neutral Gardening (MWNG) which aims to reduce reliance on mains water (MW) without compromising landscape opportunities and plant performance. It draws on the findings developed from a review of the literature identified in Chapter 2. It goes beyond the existing work done by others by fully integrating a range of lot-scale alternative water sources and other measures in order to meet the water demand of a sustainable urban garden.

First, MWNG is defined and the key principles described in Section 3.2. Details of the technical and regulatory parameters that guide its application are outlined in Section 3.3. Section 3.4 introduces the process by which the concept was tested and verified via three real-life case study gardens which are presented in the following chapters.

3.2 MAINS WATER NEUTRAL GARDENING DEFINED

MWNG is a term coined by the author as part of this study for a new site-responsive, integrated approach to water system design and management in residential gardens. The approach integrates available lot-scale water sources – such as greywater (GW), rainwater (RW) and groundwater (GndW) – with efficient irrigation practices and local environmental conditions to establish a holistic water budget that is capable of meeting plant water demand as part of a water-sensitive landscape design. The concept is based on the following principles and approaches to water source utilisation that build on concepts identified in the previous chapter:

1. A garden is divided into hydrozones (Hzs) (Thayer & Asler, 1984) where plants are grouped together based on common water demand and water quality requirements so they can be matched with a suitable water supply stream and water demand volumes can be accurately estimated.

2. GW reuse is undertaken in line with relevant local regulatory guidelines (e.g. Department of Health, 2010). Realistic GW generation volumes are calculated to establish whether plant water demand requirements are likely to be met based on available volumes. Design responses to GW water deficit include either selecting plants with a compatible water demand, or allowing for supplementary irrigation to meet the deficit (Byrne *et al.*, 2008).

3. RW harvesting (where climatically suitable) can provide a source of water for Hzs not suited to GW application (e.g. ground level vegetables and herbs), or GW sensitive species (e.g. alkaline intolerant) (Department of Health, 2010). RW should also be used for internal uses (non-potable uses such as toilet and washing machine as a minimum) to utilise this resource when it is not required for irrigation (National Water Commission, 2008b; Sharma *et al.*, 2015). Tank sizing is determined via daily time-step supply–demand side modelling (at a minimum) incorporating local rainfall data, plus available roof catchment area and household demand (Hunt *et al.*, 2011b).

4. GndW can be used as an additional source of irrigation water where it is available and when it can be demonstrated that its use can be replenished through local rainfall recharge at the site catchment level (Department of Water, 2009).

5. MW is to be used for irrigation only where it can be offset by the use of RW for internal uses during wet weather periods, during which time it can be assumed that RW is available but not required for irrigation. Current industry standard water efficiency benchmarks for both hardware and irrigation are assumed (Australian Building Codes Board, 2015; IA, 2012).

6. Additional garden areas outside the established 'Mains Water Neutral' water budget are designated as unirrigated plantings, with plant species being chosen on the basis of being able to survive on local rainfall alone.

3.3 MAINS WATER NEUTRAL GARDENING METHODOLOGY

The following section details the methodology underpinning the MWNG model, including: (1) estimating garden water requirements; (2) meeting plant water demand with GW; (3) determining RW yield; and (4) establishing sustainable GndW extraction and recharge rates. Finally, a MWNG model schematic is provided to illustrate the interrelationship between sources and demands, as well as the operational parameters for achieving MW neutrality.

3.3.1 ESTIMATING GARDEN WATER REQUIREMENT

Garden Water Requirement (GWR) can be calculated by totalling the estimated water demand of each Hz in a garden that requires supplementary watering. Hydrozone Water Demand (HzWD) can be estimated by first establishing the daily Plant Water Demand (PWD) for a specific Hz by assigning it a nominal plant Crop Factor (CF) (i.e. amount of water that a plant transpires in relation to evaporation [Keller and Blessner, 2014]) and multiplying this by the local evaporation rate (average daily by month). The HzWD can then be calculated by multiplying the daily PWD with an allowance for the efficiency of the irrigation system (IEf) servicing the Hz, then accounting for the size of the area (Ar). That is:

GWR (L/day) = ∑ of all HzWD

where:

HzWD (L/day) = PWD x IEf x Ar

where:

PWD (mm/day) = CF x ER

where:

CF = crop factor (factor of 1)
ER = local daily evaporation rate (mm)
IEf = irrigation system efficiency factor (%)
Ar = area (m^2)

Table 2: Modelling inputs for estimating garden water demand (adapted as noted).

Hydrozone	**Crop factor**[1]	**Local daily evaporation (nominal summer month)**	**Irrigation system efficiency**[2]	**Area (m^2)**	**Hydrozone water demand (L/day)**
Annual vegetables, herbs & flowers	0.8 – 1	10mm	95% (drip)	10	84
Trees (tender)	0.7 – 0.9	10mm	95% (drip)	10	73.5
Trees, shrubs & groundcovers (hardy)	0.4 – 0.6	10mm	95% (drip)	20	84
Mixed perennial plantings, including fruit trees, shrubs & groundcovers	0.5 – 0.7	10mm	95% (drip)	20	120
Lawn (warm season)	0.5	10mm	80% (sprinklers)	25	150
Native shrubs, groundcovers & grasses	0.2 – 0.4	10mm	95% (drip)	30	94.5
Garden water requirement (L/day)	–	–	–	–	696

[1] Adapted from WAWRC, 1986; Costello *et al.,* 2000; Keller, J. & Bliesner, D., 2014 Connellan, 2013.
[2] Keller, J. & Bliesner, D., 2014.

Table 2 provides a working example of how GWR can be estimated based on typical Hzs incorporating common categories of garden plants. The CF has been provided for each Hz, along with a nominal daily ER and IEf, and the resulting HzWD, assuming full canopy coverage.

Watering Frequency (WF) also needs to be established for inputting into a daily time-step model. The interval (in days) between watering events is based on the Water Usage Rate (WUR) at which the plants transpire the available moisture within their root zone, i.e. the Soil Water Reservoir (SWR). The SWR can be estimated by multiplying the Soil Moisture Holding Capacity (SMHC) of the site soil by the Average Root Depth (ARD) of the plants in a particular Hz. The rate at which it is used can be determined by multiplying the CF by the daily ER.

That is:

WF (days) = SWR / WUR
SWR (mm/m) = SMHC x ARD
WUR (mm/day) = CF x ER
where:
SMHC = Soil Moisture Holding Capacity (mm/m)
ARD = Average Root Depth (m)
CF = Crop Factor (factor of 1)
ER = Evaporation Rate (mm/day)

The length of watering time is dependent on the application rate of the irrigation system (i.e. volume of water applied over area in mm/hr). This will typically vary across Hzs where different water sources are used (based on differing flow rates), and where different emitter types and emitter spacing are used.

3.3.2 MEETING PLANT WATER DEMAND WITH GREYWATER

In Hzs where GW is applied, it is important to match HzWD with expected GW production volumes, in addition to selecting plants suited to the specific water quality characteristics of GW. As outlined in Chapter 2, Section 2.4.1, the sizing of GW dispersal fields is an important regulatory requirement for the installation and operation of many types of GW systems (greywater diversion devices in particular), however actual GW volumes generated are likely to be less than the estimated design volumes as the result of under occupancy and/or improved indoor water use efficiency.

Figure 2 plots the estimated GW volumes generated from a three-bedroom home (based on Department of Health, 2010) with various occupancy scenarios against the water demand of high-water-use plants such annuals (crop factor 0.8), and medium-water-use plants such as turf (crop factor 0.5). Volumes are presented in mm/day. The graph shows that the water requirements of medium-water-use plants will be met in all occupancy scenarios, however three or more occupants are required to meet the peak water demand for high-water-use plants during the period from November to March in Perth.

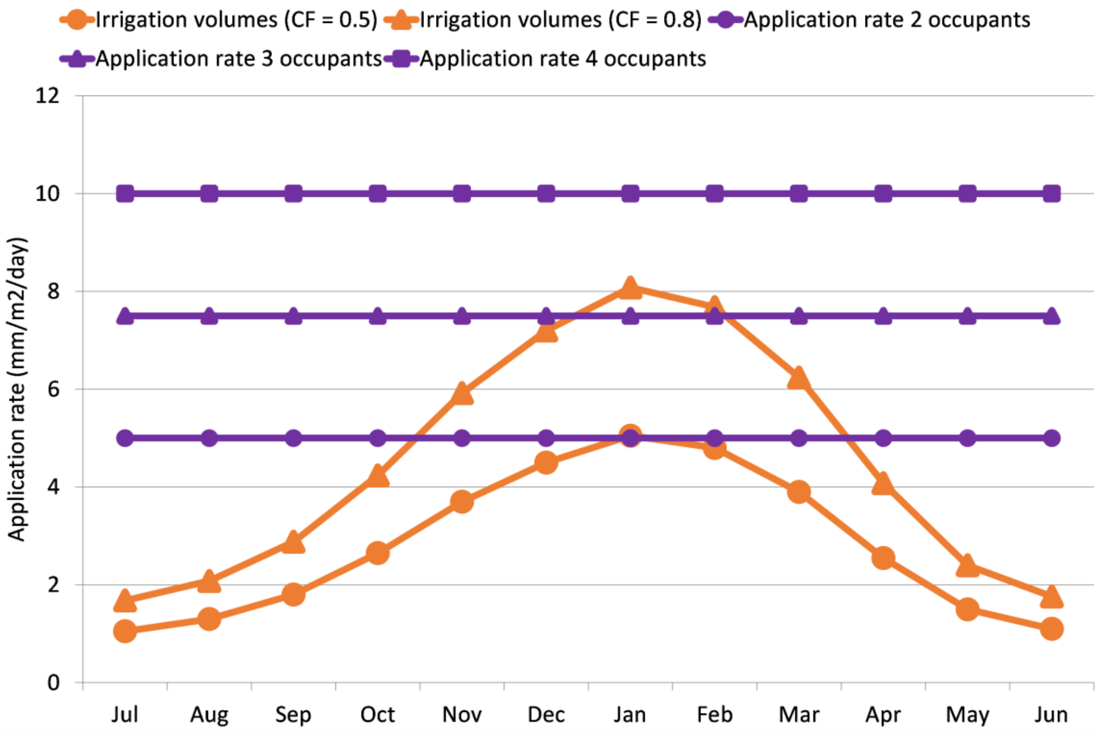


Figure 2: Water demand of medium and high-water-use plants across the year against the greywater application rate from a three-bedroom house with two, three and four occupants (location of Perth, Western Australia).

Figure 3 compares the reduced daily GW volumes from Department of Health (2010) resulting from improved water use efficiency against plant water demand for medium and high-water-use plants for a three-person house with different occupancy scenarios. Volumes are presented in mm/day. The reduced volumes are based on a 49% reduction in laundry GW by replacing top-loading washing machines with front loaders (Patterson, 2004) and a 35% reduction in bathroom GW by installing water-efficient shower and tap fixtures (from 14L to 9L per minute and 9L to 6L per minute respectively) (Byrne *et al.*, 2008).

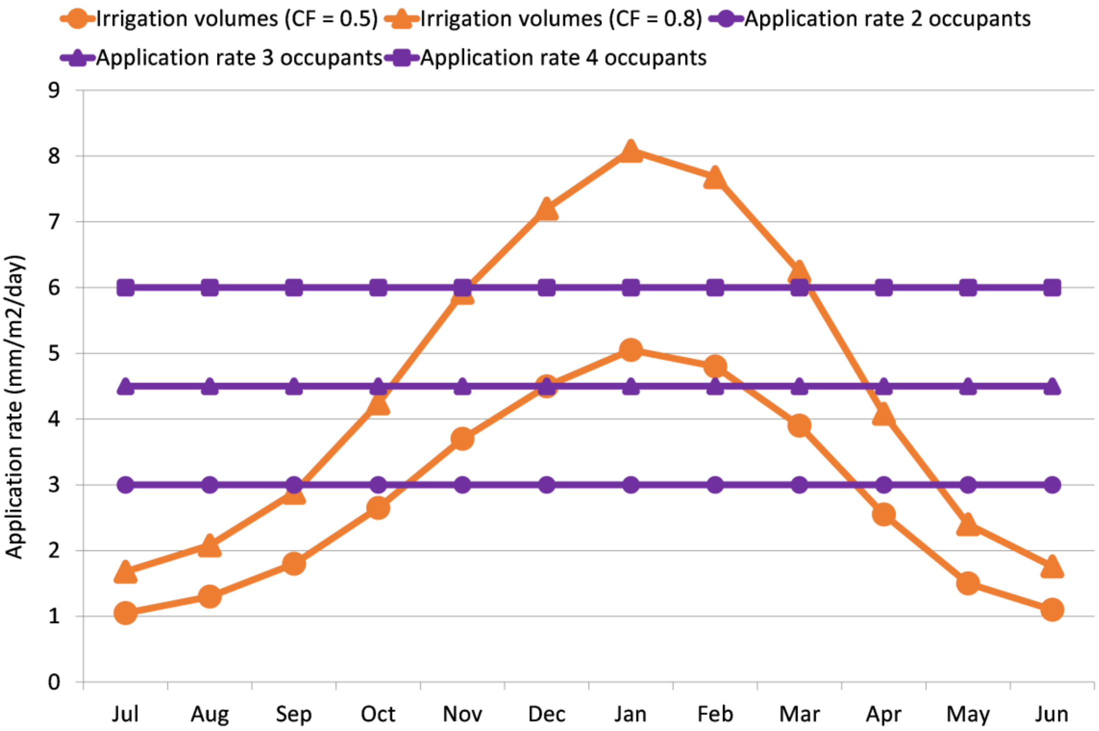


Figure 3: Water demand of medium and high-water-use plants across the year against the greywater application rate from a three-bedroom house with improved water efficiency with two, three and four occupants (location of Perth, Western Australia).

Actual household occupancy and the accuracy of average daily GW generation figures clearly have a big impact on the effectiveness of a GW reuse system to successfully meet garden irrigation needs. Figure 4 shows the cumulative water requirements to supplement the irrigation deficit for high-water-use plants (crop factor 0.8) for the GW generation scenarios in Figures 2 and 3. Volumes are presented in mm/m^2/day. For the three-bedroom house, supplementary irrigation requirements range from 3.7kL with four occupants, to 20.2kL with two occupants per year.

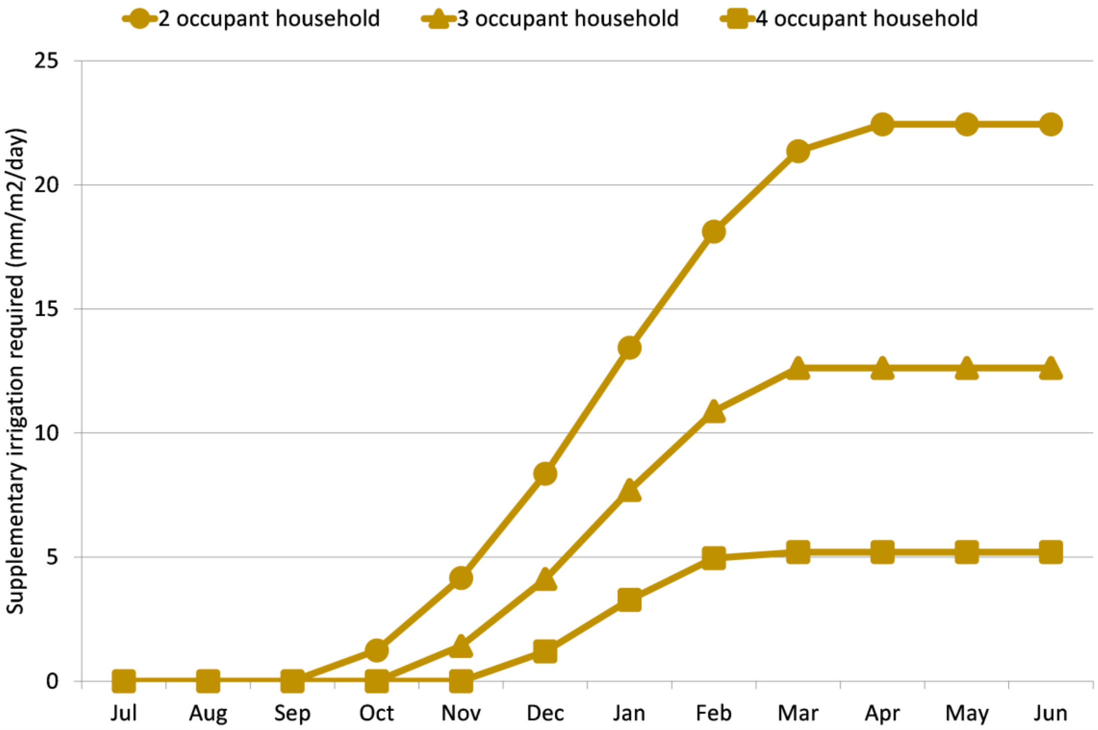


Figure 4: Cumulative supplementary irrigation requirements for a three-bedroom house (improved water efficiency) with two, three and four occupants (location of Perth, Western Australia).

The GW volume deficits need to be accounted for in the landscape water budget and a supplementary source identified. Consideration also has to be given to the method of augmentation – i.e. top-up of GW supply via the GW system, or through the use of a secondary irrigation system. These are further explored in the following case study chapters.

3.3.3 RAINWATER YIELD

RW Yield (RWY) can be determined by multiplying Rainfall (Rf) by the Effective Roof Catchment (ERC), divided by demand over time, where:

RWY = RW Yield (L/day)
Rf = Rainfall (mm) taken from the nearest meteorological station
ERC = Effective Roof Catchment (m^2) x Catchment Efficiency Coefficient[1]
D = Demand (L/day)

[1] The catchment efficiency coefficient allows for losses from gutter overflow and other spillage which reduces the volume being captured for use and are typically included in RW harvesting models (Coombes and Kuczera, 2001; Mitchell, 2001; Hunt *et al.*, 2011b). The coefficient applied will vary depending on type and quality of roofing and compliance to roof plumbing drainage codes.

A supply–demand side modelling tool (e.g. Hunt *et al*., 2011b) can be used to inform RW yield and tank overflow values for various tank storage size scenarios. As identified in

Chapter 2, Section 2.4.2, there are a number of modelling tools (including open source online RW tank sizing calculators) available which can be used to perform this function.

Key input requirements will include irrigation requirements (if applicable) as outlined in Section 3.3.1, plus internal demands to be serviced by RW, such as toilet flushing and washing machine use. Per person usage should be sourced from local standards or water use studies (e.g. Water Corporation, 2010) and multiplied by expected occupancy. Reductions in volumes based on additional water efficiency measures should also be taken into account. Working examples are provided in the following case study chapters.

3.3.4 GROUNDWATER EXTRACTION & RECHARGE

GndW can be considered a sustainable source of fit-for-purpose water provided it is of suitable quality and its extraction is replenished. For the purpose of this model, sustainable extraction is defined by a water balance that demonstrates that it is recharged by direct infiltration on-site within a typical year (Department of Water, 2009). Allowances need to be given to RW that is taken out of the system flow (i.e. where it is either consumed, used for irrigation, or disposed of by sewer), as well as losses to run-off and evaporation/evapotranspiration. That is:

Sustainable extraction ≤ direct on-site infiltration where:

Infiltration = AARF x APS x GDWIF + (AARF x RA – RWY) (or TO if known)
AARF = Average Annual Rainfall (mm)
APS = Area of Permeable Surfaces (m^2)
GDWIF = GndW Infiltration Factor (%)
RA = Roof Area m^2
RWY = RW Yield (L)
TO = Tank Overflow (L)*

*Assuming the tank overflow goes to onsite infiltration.

3.3.5 MAINS WATER NEUTRAL GARDENING MODEL SCHEMATIC DIAGRAM

Figure 5 identifies the available water flows considered in the MWNG model via a schematic diagram. Supply side flows are shown as solid line work and demand side flows are shown as dashed line work. In summary the design assumptions are as follows:

1. MW outside demand (MWOD) must be ≤ than RW inside demand (RWID).
2. GndW extraction (GDWE) must be ≤ than GndW infiltration (GDWI).
3. GW applied (GWA) can be supplemented by either RW (if available), GndW (if available and ≤ GDWI), or MW (if ≤ RWID).

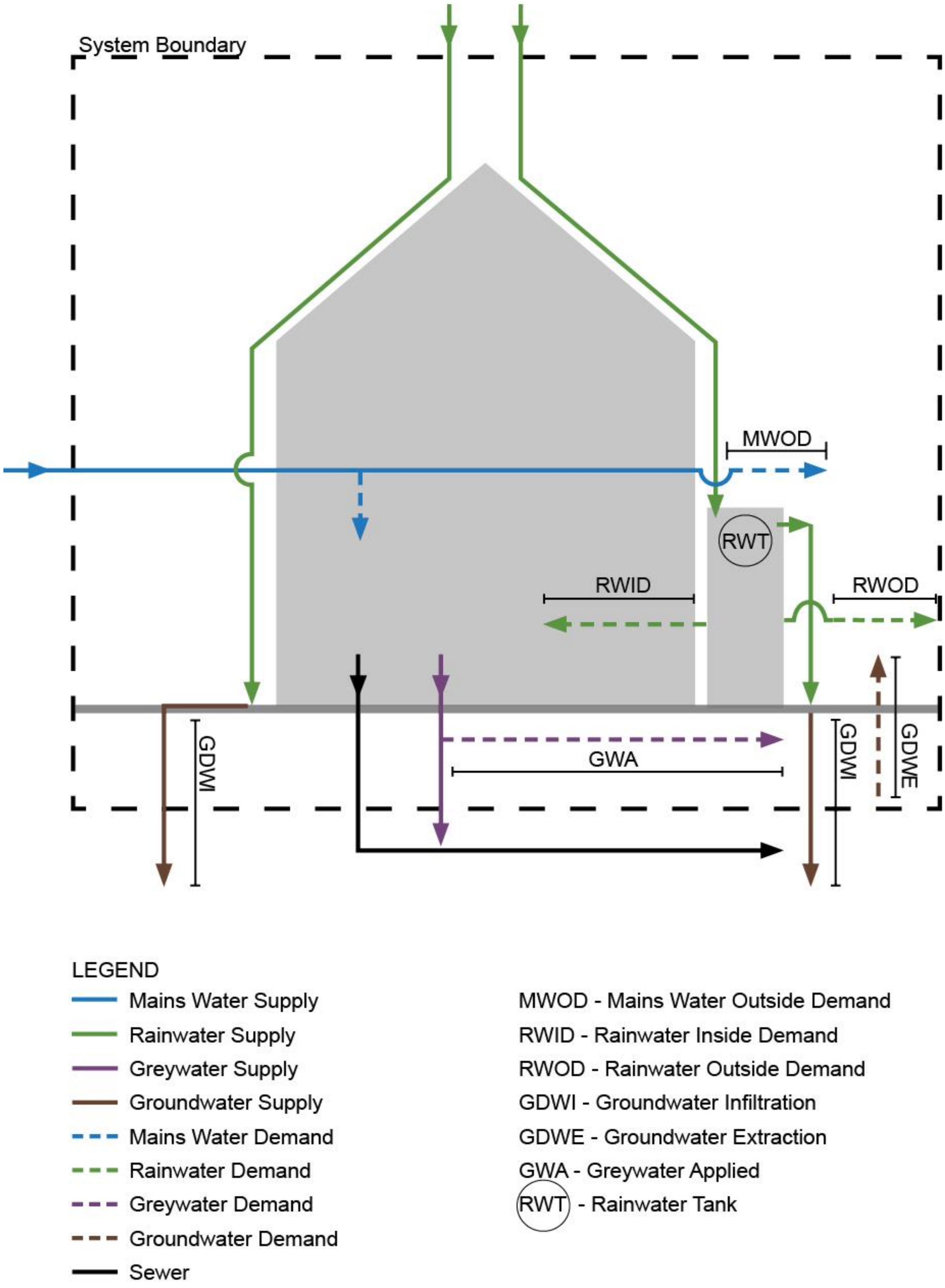


Figure 5: Mains Water Neutral Gardening concept schematic showing water flows in and out of a residential lot-scale system.

3.4 MODEL TESTING & VERIFICATION

The following chapters (4 to 6) describe the testing of the MWNG model via three case study gardens designed and built by the author over a ten-year period. In each instance, the sizing of landscape Hzs was done with careful consideration of the available water volumes whilst addressing the sustainability goals of the Sustainable Urban Gardening (SUG) framework outlined in Chapter 2, Section 2.2. Each project represents a slightly different application of the MWNG model, with varying configurations of RW, GW and GndW utilisation. An overview of each property, plus insights into the design intent behind each project, is provided at the beginning of the respective chapters.

Detailed modelling of expected GW volumes, garden water demand, RW yield and GndW recharge and extraction rates was undertaken in line with the methods outlined in this chapter. After establishment of the gardens, a period of monitoring was undertaken to: (1) assess the performance of the water systems installed; (2) verify whether the MWNG objective had been achieved; and (3) compare ‘real life’ data versus ‘modelled’ data to test the assumptions of the MWNG model and inform how they could be improved. The monitoring methodology and results are presented at the end of each chapter.

The case study gardens were designed and built in chronological order so the practical learnings from one informed the next. Insights into the lessons learned by the author from each of the projects is provided at the end of the corresponding chapter, along with a summary of water system costs and basic financial analysis. Comparative analysis of the findings from all three case studies is provided in Chapter 7 (Discussion) to address the research questions presented in Chapter 1.

CHAPTER 4: CASE STUDY 1

4.1 CHAPTER INTRODUCTION

This chapter covers the first of three case study gardens (CS1) that were designed and built by the author as part of this study based on the Sustainable Urban Gardening (SUG) and Mains Water Neutral Gardening (MWNG) concepts. The chapter begins with an overview of CS1 (Section 4.2) followed by a description of the landscape design and SUG attributes (Section 4.3).

Section 4.4 describes the water system infrastructure installed, including greywater (GW), rainwater (RW) and irrigation systems. Section 4.5 presents the water balance modelling underpinning the MWNG landscape design, including estimated GW volumes, garden water requirement and RW yield, as well as the projected MWNG outcome

Section 4.6 describes the water usage monitoring undertaken post garden establishment, including equipment and techniques used. The results and analysis of the findings are described in Section 4.7 and details on lessons learned from this case study are provided in Section 4.8. Further discussion is provided in Chapter 7 (Discussion), along with the other two case studies for comparison.

4.2 CASE STUDY OVERVIEW

CS1 is a two bedroom, one bathroom, semi-detached dwelling located on a 330m^2 block in the Perth suburb of South Fremantle, Western Australia, where the local climate type is classified as Mediterranean (Bureau of Meteorology, 2015) and the soil type is coarse sand, typical of the Karrakatta soil association of the Spearwood dune system of that area (McArthur, 2004).

The house was built in 1906, but had undergone major renovations by the owners around 2003/4 which included the installation of BCA-compliant, WELS-rated, water-efficient plumbing fixtures. Originally the property was serviced solely by mains water (MW) to supply all demands, and mains sewer for wastewater disposal. The arrangement of the existing plumbing allowed for relatively easy access to bathroom and laundry GW sources for diversion and reuse, plus connection of RW supply to the existing toilet and washing machine, as well as future garden irrigation and garden tap. More information on the equipment installed at CS1 is provided in Section 4.4 (Water System Infrastructure).

The author (and partner) lived at the property throughout the landscape design, construction and commissioning period, handing the property back to the owners once the garden was fully completed and established, but prior to detailed monitoring commencing. Following this, occupancy varied between one to three persons during the monitoring period. The occupants were between the ages of 21 and 30 years and included both males and females. Further details are presented in Section 4.6 (Monitoring) and Section 4.7 (Results and Analysis).

4.3 LANDSCAPE DESIGN

4.3.1 DESIGN INTENT & PROJECT INSIGHTS

The brief for the landscape design (established between the author and the property owners) was to create a productive, water-efficient garden, whilst enhancing outdoor living opportunities. A studio was to be included at the rear of the garden to serve as an additional bedroom or study. The remainder of the landscape was to be dedicated to features that would contribute to the liveability and sustainability of the household, including shade, food production, water efficiency and visual amenity in line with the author's SUG framework.

A key motivation for the author in selecting this property was the challenge of demonstrating how the appropriate SUG design elements and supporting gardening activities could be deployed despite space limitations. The GW and RW tanks were located in-ground under decking to save space, and features carefully chosen to provide multiple functions, such as trellised fruit trees on the boundary fences to provide privacy screening in addition to seasonal fruit (see Photo 5B, page 45), or a worm farm mounted in a frame with a lid and located where it could also be used as a potting bench (see Photo 2A, page 43). The verge area was also utilised by planting it with local native species to support the SUG biodiversity and habitat restoration goal (see Photo 3A, page 44).

The relatively small size of the garden (in comparison to the author's previous suburban garden projects) provided initial motivation to design a garden that would not be reliant on MW, with the intention to match the irrigated areas to anticipated GW volumes (for trees and shrubs) and RW (ground-dwelling vegetables and herbs). It soon became evident that whilst GW volumes were likely to be adequate, RW volumes would not be adequate to meet year-round demand given the space constraints and cost implications of underground storage. It was at this point that the MWNG concept was created, and the areas to be irrigated with MW (i.e. vegetables, herbs and small habitat ponds), would be limited to what could be offset by internal MW substitution with RW during rainy periods. In effect, the property would display the same MW usage as a property without a garden (or where no MW is used outside), assuming similar occupancy rates and water use behaviours.

4.3.2 SUSTAINABLE URBAN GARDENING FRAMEWORK & DESIGN RESPONSE

Table 3 provides a summary of the key landscape design elements and supporting gardening activities at CS1 in response to the SUG framework developed by the author. The landscape design prepared for the property is presented as Figure 6. Where relevant, an alphanumeric reference has been listed alongside the landscape design elements in the table correlating to their location on the landscape plan. Photographs are provided in Figure 7 for further context and detail, using the same reference key.

Table 3: Summary of the sustainable landscape design elements and supporting gardening activities at case study 1 based on the Sustainable Urban Gardening framework.

SUSTAINABILITY GOAL 1: ENERGY EFFICIENCY	
Desired Outcomes	**Design Elements & Supporting Gardening Activities**
Reduced fossil fuel use from embedded energy in materials and in the operations of the house and garden.	Shading structure to northern side of house, angled to allow in winter light (1A). Repurposed materials used where possible including timber, paving and aggregates (1B). Studio and surrounding landscape structure designed to capture cooling winds (1C).
SUSTAINABILITY GOAL 2: ORGANIC WASTE RECYCLING & SOIL MANAGEMENT	
Desired Outcomes	**Design Elements & Supporting Gardening Activities**
Local soil carbon regeneration and nutrient recycling.	Composting bins and worm farm to recycle house and garden organic waste (2A). Soil conditioning and mulching to increase soil carbon and naturally improve soils over time (2B).
SUSTAINABILITY GOAL 3: BIODIVERSITY & HABITAT RESTORATION	
Desired Outcomes	**Design Elements & Supporting Gardening Activities**
Enabling indigenous plant, insect and animal life to thrive.	Considered plantings (native and exotic) to provide food source for insects and birds (3A). Habitat structures including bird and micro bat nesting/roosting boxes (3B). Water features for invertebrate, fish and frog habitat (3C). Deep mulching and leaf litter accumulation to encourage invertebrates and bird foraging (3D).
SUSTAINABILITY GOAL 4: ORGANIC PEST & DISEASE MANAGEMENT	
Desired Outcomes	**Design Elements & Supporting Gardening Activities**
Achieving natural ecosystem functioning that controls pests and weeds without toxic chemical use.	Companion planting to encourage predatory insects and pest distraction (4A). Design allows for crop rotation of vegetables (4B). Design allows for effective deployment of cultural practices for organic pest and weed control (4C).

SUSTAINABILITY GOAL 5: FOOD PRODUCTION	
Desired Outcomes	**Design Elements & Supporting Gardening Activities**
Local food production contributing to household food supply.	Space allocated for intensive vegetable growing (5A). Fruit tree trellis system on fence line (5B). Diverse range of edible herbs included in feature pots (5C) Edible aquatic plants included in water features (5D) Poultry for eggs (5E)
SUSTAINABILITY GOAL 6: WATER CONSERVATION	
Desired Outcomes	**Design Elements & Supporting Gardening Activities**
Reducing water-based ecological footprint.	Effective hydrozing for effective irrigation management (refer Figure 8). Efficient irrigation system (6A). GW applied to appropriate hydrozone (Hz) (6B). RW harvesting to meet part of the irrigation demand, plus non-potable indoor uses to offset MW use for irrigation (6C). Water efficient gardening practices deployed, including soil building, mulching and plant selection/care (refer Appendix 1).
SUSTAINABILITY GOAL 7: HEALTH & WELLBEING OF HOUSEHOLDERS	
Desired Outcomes	**Design Elements & Supporting Gardening Activities**
Achieving a liveable housing habitat, including daily contact with nature.	Landscaping enhances thermal performance for house, increasing occupant comfort (7A). High quality outdoor living areas providing regular contact with garden (7B). Fresh food available from garden (7C).

Figure 6: Landscape plan for case study 1.

Figure 7: Photographs of case study site 1 (photo credits: M. Ward; A. Lambert; R. Frith; P. Jauncey; J. Byrne).

1A: Repurposed materials used where possible including timber, paving and aggregates.

1B: Shading structure to northern side of house, angled to allow in winter light and provide summer shade.

1C: Studio and surrounding landscape structure designed to capture cooling winds.

2A: Composting bins and worm farm to recycle house and garden organic waste.

2B: Soil conditioning and mulching to increase soil carbon and improve soils.

3A: Considered plantings to provide food source for insects and birds.

3B: Habitat structures including bird and micro bat nesting/roosting boxes.

3C: Water features for invertebrate, fish and frog habitat.

3D: Deep mulching and leaf litter to encourage invertebrates and bird foraging.

4A: Companion planting to encourage predatory insects and pest distraction.

4B: Garden beds allow for crop rotation of vegetables.

4C: Design allows for effective deployment of cultural practices for organic pest and weed control.

5A: Spaces for intensive vegetable growing.

5B: Fruit tree trellis system on fence line.

5C: Diverse range of edible herbs included in feature pots.

5D: Edible aquatic plants included in water features.

5E: Poultry for supply of eggs.

6A(i): Irrigation system – valve manifold.

6A(ii): Irrigation system – controller.

6A(iii): Irrigation system – soil moisture sensor.

6A(iv): Irrigation system – dripline.

6A(v): Irrigation system – pot drippers.

6B(i): Greywater system – settlement and pump out tanks.

6B(ii): Greywater system – pump out tank.

6B(iii): Greywater system – filter and meter.

6B(iv): Greywater system – dripline.

6C(i): Rainwater system - tank.

6C(iii): Rainwater system – mains water backup valve.

6C(ii): Rainwater system – rain head with leaf screen.

7A: Landscaping enhances thermal performance of the house, increasing occupant comfort.

7B: High quality outdoor living areas providing regular contact with the garden.

7C: Fresh food available from the garden.

4.4 WATER SYSTEM INFRASTRUCTURE

4.4.1 GREYWATER REUSE SYSTEM

The greywater diversion device (GDD) at CS1 was a proprietary system known as the ‘GRS Water Save’ by GW Reuse Systems Pty Ltd (WA Department of Health approval number GW0403) which was installed as per the WA Department of Health *Code of Practice for the Reuse of GW in Western Australia* (Department of Health, 2005).

The system consisted of two concrete tanks, with the first tank being for collection and settlement of the GW, and the second tank being a pump out chamber. The tanks were sized to hold GW for a period of up to 24 hours. As newly generated GW flowed into the collection tank, the retained GW flowed into the second tank with a submersible pump activated by a level switch once the set point was reached. The pressurised water was pushed through a coarse filter pad prior to being applied to designated garden areas via dripline irrigation in accordance with Department of Health (2005) guidelines. In the event of pump failure or filter blockage, the system would direct GW overflow to sewer.

Photographs of the key features and general arrangement of the GW system installed at CS1 are shown in Figure 7, photos 6B(i)–6B(iv) (page 47).

4.4.2 RAINWATER HARVESTING SYSTEM

The RW harvesting system installed at the study site was done in accordance with *AS/NZS 3500 Plumbing and Drainage – Water Services* (Standards Australia, 2003), and in line with the *Rainwater Tank Design and Installation Handbook* (National Water Commission, 2008a).

Rain was harvested off 200m^2 of roof catchment (the entire house roof area) via a typical roof guttering and ‘dry-feed’ gravity drained pipework arrangement where the pipes direct water from the gutters to the tank via gravity and drain empty after each rain event. Leaf traps and first flush devices with manual drain valves were located on all gutter pops to prevent debris from entering the tank.

RW was stored in a 3,500L in-ground polyethylene RW tank with the overflow diverted to a soakwell. The RW tank was fitted with a float switch–activated submersible pressure pump. Pressurised RW was supplied to end-use fixtures and appliances (toilet, washing machine, irrigation system and garden taps) via a MW backup valve. The backup valve preferentially directed RW on demand when available, and supplied MW as back-up.

Photographs of the key features and general arrangement of the RW harvesting system as installed at the case study site are shown in Figure 7, photos 6C(i)–6C(iii) (page 48).

4.4.3 LANDSCAPE HYDROZONES & IRRIGATION SYSTEM

The landscape design at CS1 was based on five Hzs as identified in Figure 8, with size and location of the various Hzs being determined by the designer's response to available water, and prioritisation of gardening activities in line with the SUG framework.

The GW Hz (Hz1) receives water from the GW system, which discharges on a volumetric basis once the pump level switch is triggered, as described in Section 4.5.1. Plant selection included a range of species suited to untreated GW (Department of Health, 2010). Other Hzs include Vegetables Hz (Hz2); Pots (Exposed) Hz (Hz3), which are exposed to sun and rain; Pots (Protected) Hz (Hz4), which are located under eaves so are partially shaded and sheltered from rain; and Native (Dryland) Hz (Hz5) which is unirrigated.

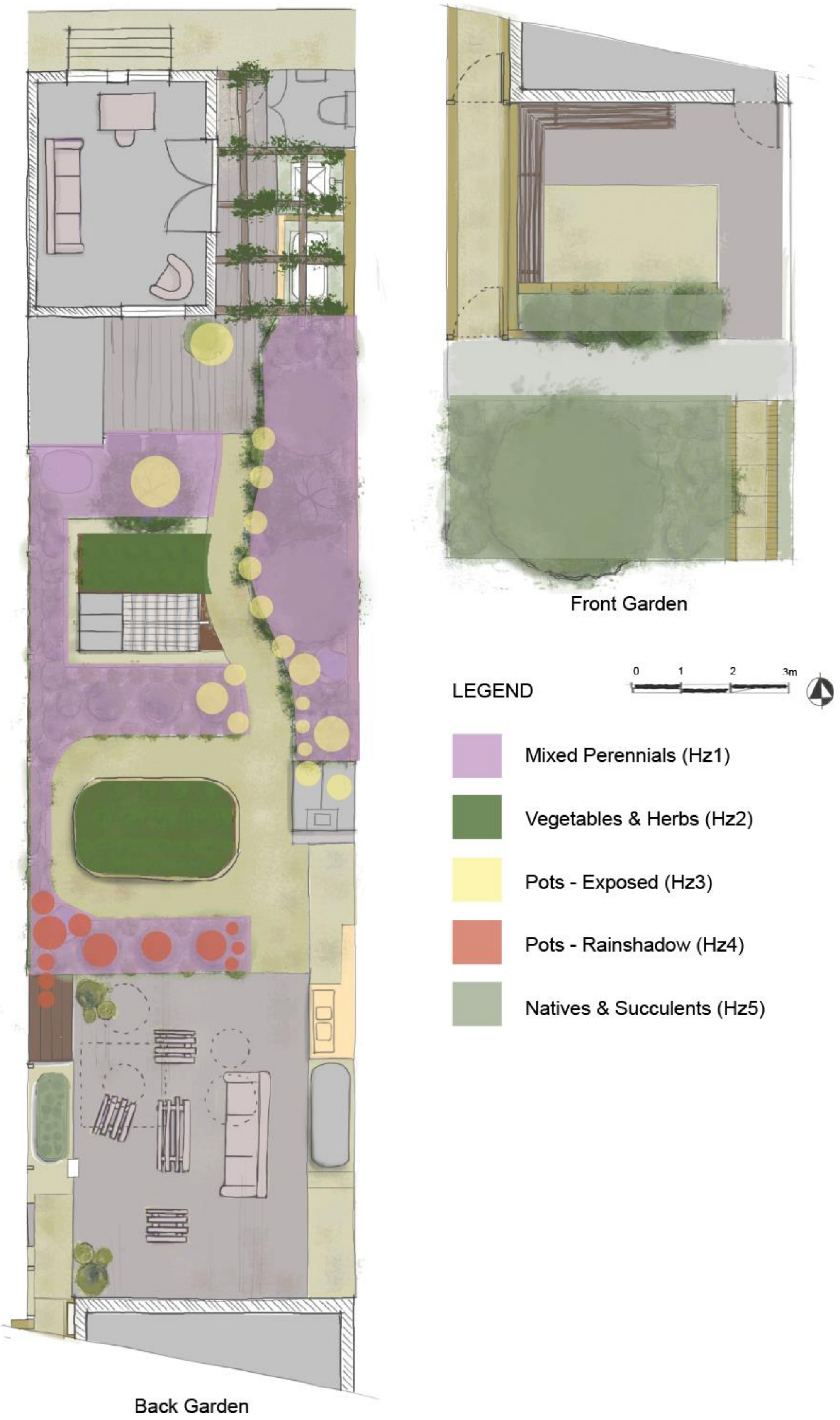


Figure 8: Hydrozone plan for case study 1.

The timing of watering to Hz2, Hz3 and Hz4 is automated via a multi-station programmable irrigation controller fitted with a capacitance soil moisture sensor to reduce unnecessary irrigation events. The controller was also used to operate a dedicated GW ‘top-up’ line to supply RW and MW for periods when the house is unoccupied and irrigation is required, or when GW volumes are inadequate to meet plant water demand. The top-up entry point was via a sink trap and essentially replicates through GW flows through the system.

The design and installation of the irrigation system was undertaken in accordance with relevant irrigating industry standards (Cape, 2006).

Photographs of the key features and general arrangement of the irrigation system as installed at the case study site are shown in Figure 7, photos 6A(i)–6A(v) (page 46).

4.4.4 WATER SYSTEM INTEGRATION

Figure 9 shows the integration of MW, GW and RW, including water flows from source to sink. MW is the sole service supplying the internal potable demands, including kitchen taps and dishwasher, bathroom taps and shower, and laundry taps. RW supplies internal non-potable demands, including toilet and washing machine, plus external water demands, including irrigation to Hz2, Hz3 and Hz4, garden taps and GW top-up. If RW is unavailable, then these demands will be met by MW via the MW backup valve. GW generated from the shower, bathroom basin, laundry basin and washing machine is applied to Hz1.

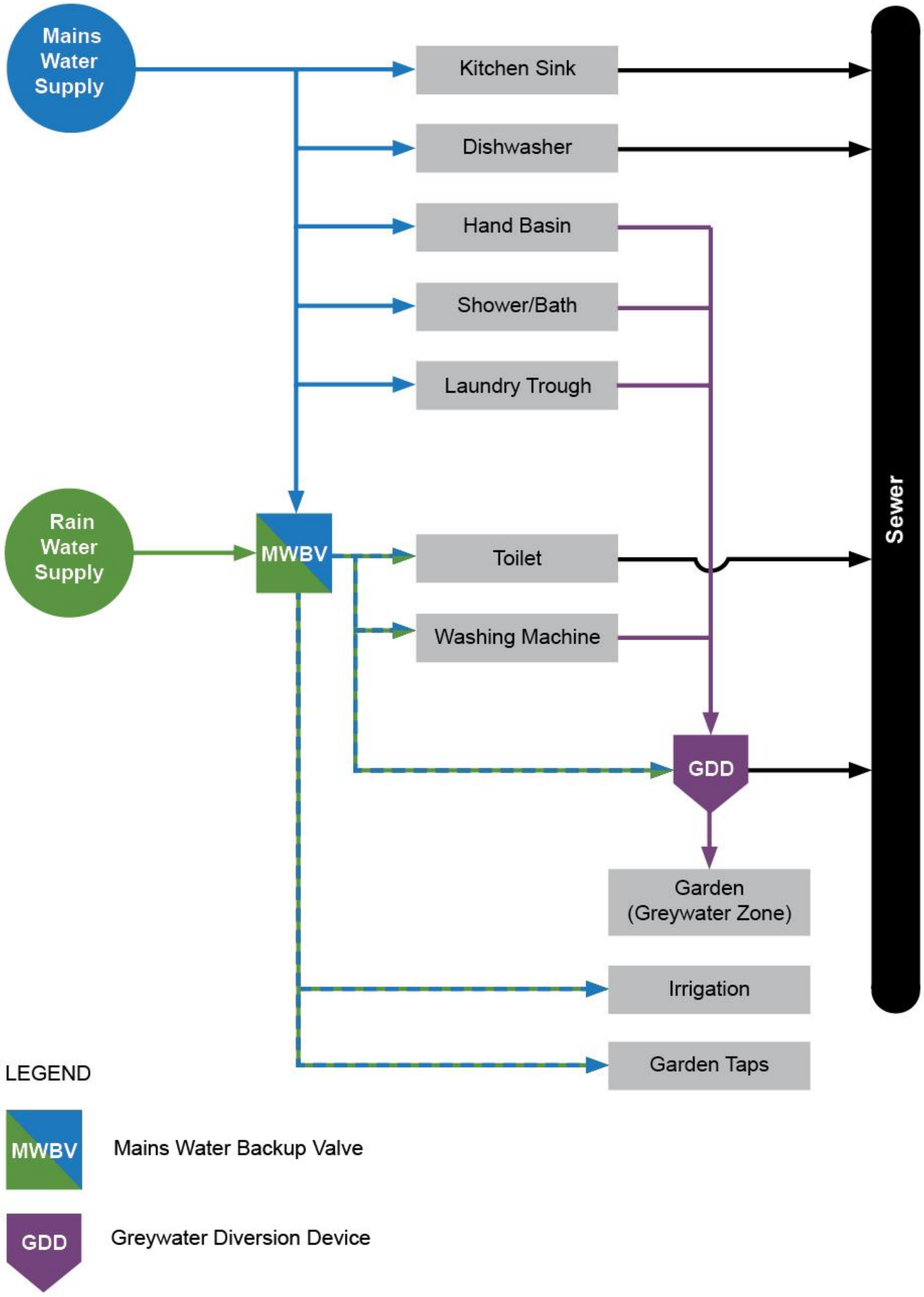


Figure 9: Water system design schematic illustrating the integration of the various water sources at case study 1, including water flows from source to sink.

4.5 WATER BALANCE MODELLING

The following section outlines the water balance modelling for CS1 undertaken at the design phase using a tailored spreadsheet tool developed by Hunt *et al.* (2011b). The modelling included estimation of GW volumes, irrigation demand and RW yield based on the MWNG objective.

4.5.1 GREYWATER VOLUMES

Table 4 presents the Department of Health (2005) estimated daily GW generation volumes, as well as what was likely to be generated using water-efficient fixtures, assuming a 49% reduction in laundry GW achieved by replacing top-loading washing machines with front loaders (Patterson, 2004) and a 35% reduction in bathroom GW by installing water-efficient shower and tap fixtures (from 14L to 9L per minute and 9L to 6L per minute respectively) (Byrne *et al*., 2008).

Table 4: Regulatory greywater design volumes compared to estimated volumes for case study 1.

GW source	Design volumes* (L/person/day)	Water efficient volumes (L/person/day)	Water efficient volumes (L/day = 3 people)
Bathroom	51	33	99
Laundry	42	23	69
Total Volume	93	56	168

*Source: Department of Health (2005)

Figure 10 shows the estimated daily household generation of GW (168L per day) as providing an irrigation application rate of 6.2mm per day over the 27m^2 area. Running alongside is the monthly water demand of landscaping, assuming a plant crop factor of 0.6 and an irrigation application inefficiency (IEf) of 95%. It can be seen that 0.1kL GW top-up will be required.

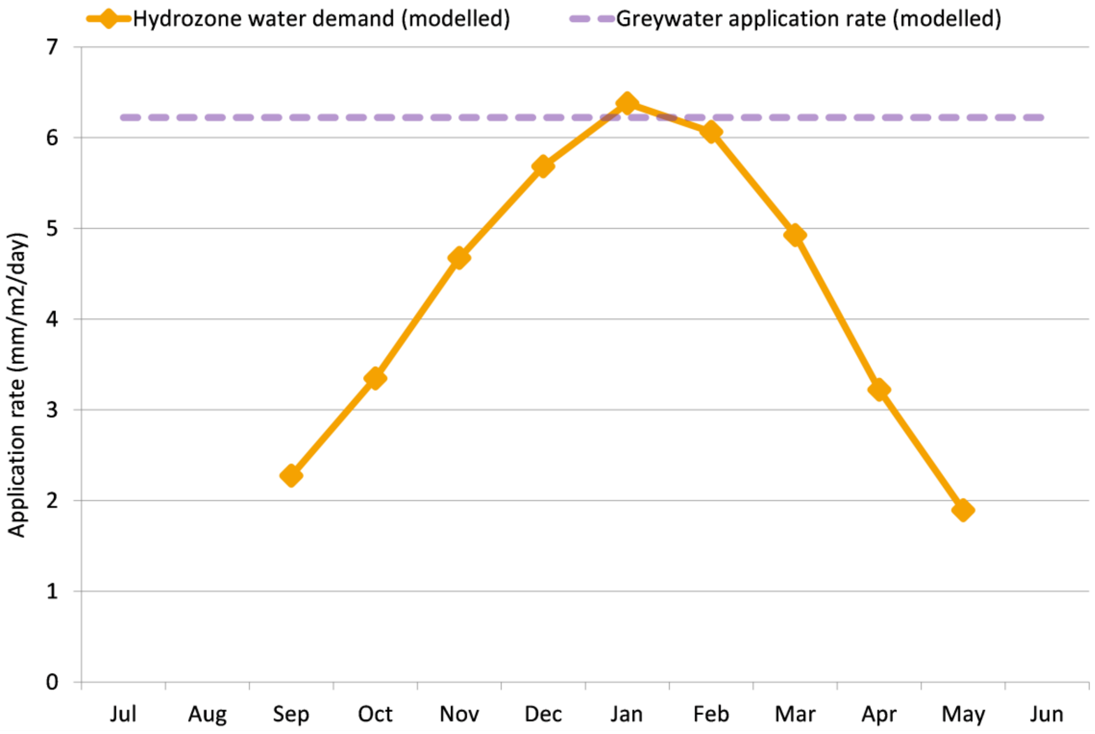


Figure 10: Estimated application rates compared with estimated hydrozone water demand (location of Perth, Western Australia).

4.5.2 IRRIGATION DEMAND

Irrigation volumes for the three Hzs serviced by RW and MW (Hz2, Hz3, Hz4) via the programmable irrigation system were calculated for the purposes of estimating landscape water demand. Table 5 outlines the key information used in the modelling for each Hz. Note: Hz3 was split across two stations to ensure adequate water pressure and flow rate (listed as Hz3a and Hz3b).

Table 5: Hydrozone irrigation demand modelling inputs for case study 1.

Parameter	Hz1 Mixed Perennials (GW)	Hz2 Vegetables	Hz3a Pots – Exposed	Hz3b Pots – Exposed	Hz4 Pots – Sheltered
Irrigation area (m^2)	27	8	2	2	2
Crop factor	0.6	0.8	0.8	0.8	0.4*
Root depth (m)	0.5	0.30	0.30	0.30	0.25
Canopy cover (%)	100	100	100	100	100
Irrigated by	GW	RW	RW	RW	RW
Then by	RW/MW	MW	MW	MW	MW

*Crop factor of 0.8 multiplied by 50% to account for shady microclimate.

Table 6 presents estimated monthly irrigation demand for each Hz based on local evapotranspiration rates.

Table 6: Estimated irrigation demand by hydrozone (kL) for case study 1.

Month	Evapo-trans. Rate* (mm/day)	Hz1 Mixed Perennials (GW)	Hz2 Vegetables	Hz3a Pots Exposed	Hz3b Pots Exposed	Hz4 Pots Sheltered	Combined (kL/month)
January	10.1	5.34	2.11	0.68	0.56	0.33	9.02
February	9.6	4.75	1.88	0.61	0.50	0.33	8.06
March	7.8	4.12	1.63	0.53	0.43	0.26	6.97
April	5.1	2.61	1.03	0.33	0.27	0.17	4.42
May	3	1.59	0.63	0.20	0.17	0.10	2.68
June	2.2	0.00	0.00	0.00	0.00	0.00	0.00
July	2.1	0.00	0.00	0.00	0.00	0.00	0.00
August	2.6	0.00	0.00	0.00	0.00	0.00	0.00
September	3.6	1.84	0.73	0.24	0.19	0.12	3.12
October	5.3	2.80	1.11	0.36	0.29	0.18	4.74
November	7.4	3.79	1.50	0.49	0.40	0.24	6.41
December	9	4.76	1.88	0.61	0.50	0.30	8.04
Total (kL/year)	-	31.59	12.48	4.05	3.30	2.03	53.45

*Bureau of Meteorology Station 009215

4.5.3 RAINWATER VOLUMES

RW harvesting modelling was performed using average daily rainfall data to ascertain the optimal size RW tank and roof catchment area required for effective RW harvesting based on the following system design parameters:

- RW is to be used for toilet flushing and filling the washing machine (cold water supply), as well as garden irrigation for selected Hzs, with automatic MW back-up.
- The minimum tank size is to be determined by the volume of RW that can be effectively used to meet toilet and washing machine demand during periods of regular rainfall, to the extent that this volume will offset the equivalent amount of MW used for external uses, effectively making this external house demand 'MW neutral'.

The modelling inputs and internal water demands are presented in Table 7.

Table 7: Rainwater harvesting modelling inputs for case study 1.

Rainfall modelling inputs	
Catchment area (m^2)	200
Catchment efficiency (%)	80
Loss to adsorption (mm/event)	0.2
Occupancy rate	3
Toilet demand (L/p/d)	22
Washing machine demand (L/p/d)	27

Table 8 presents the modelling results, including estimated RW used under the different tank size scenarios, noting there is limited increase in yield return relative to increasing the tank size, as well as reliability (percentage of time that water is available to meet demand) and satisfaction (proportion of demand met).

Table 8: Rainwater harvesting modelling outputs for case study 1, using daily time-step, supply-demand side modelling (Hunt *et al*., 2011b).

Rainfall modelling outputs	**Tank volume (kL)**				
	2.5	**3.5**	**5**	**7.5**	**10**
Total water available (kL/year)	141.2	141.2	141.2	141.2	141.2
Annual overflow (kL/year)	73.1	71.2	69.1	66.0	63.3
Efficiency + Adsorption loss (kL/year)	31.8	31.8	31.8	31.8	31.8
Average rainfall (mm/year)	706.2	706.2	706.2	706.2	706.2
Total demand (kL/year)	75.5	75.5	75.5	75.5	75.5
Reliability (time)	63%	67%	71%	76%	81%
Satisfaction (volume)	48%	51%	53%	57%	61%
RW used (kL/year)	36.3	38.3	40.3	43.3	45.9

4.5.4 MAINS WATER NEUTRAL BALANCE

Table 9 compares the internal water demand (toilet and washing machine) met by RW, with the amount of additional MW required to meet irrigation demand (including GW top-up) during periods when RW is unavailable. These volumes (kL) are presented for a range of tank sizes and the percentage of payback, or ‘MW Neutrality’ is provided.

Table 9: Mains Water Neutral Gardening water balance by tank size for case study 1.

Tank volume (kL)	**Inhouse volume supplied by RW (kL)**	**RW irrigation scheme top-up required (kL)**	**GW irrigation supplementary MW required (kL)**	**MW neutral (%)**
2.5	34.9	20.6	0.20	168
3.5	36.7	20.5	0.20	178
5	38.7	20.4	0.20	188
7.5	41.5	20.2	0.20	204
10	43.8	20.0	0.20	217

Table 9 indicates that MWNG status can be comfortably achieved with a 2.5kL tank, that is the volume of RW supplied to the toilet and washing machine exceeds the volume of MW used for irrigation (including GW top-up). The modelling also indicates the 3.5kL tank installed should exceed MWNG status at 178% volumetric payback.

4.6 MONITORING

4.6.1 MONITORING SCOPE & PURPOSE

Monitoring of CS1 was undertaken between 1 July 2010 and 30 June 2011 for the purpose of assessing the contribution of GW and RW to meeting garden water demand, and whether the volume of RW used inside for toilet flushing and washing machine use offset outside MW use, thus making the garden MW neutral.

The monitoring period was intended to capture the water use of a three-person household over the period of a year. However, several issues arose during the trial period which affected the data, most notably variation of household occupation rates, which was compounded by malfunctions of monitoring equipment. The data presented below is therefore based on sampling periods where equipment was working and reliable.

Information on the equipment and methods used is provided in the following section (4.6.2), and details on assumptions and qualifiers relating to the sampled data used and how it has been extrapolated are provided alongside the relevant data summaries in Section 4.7 (Results and Analysis).

4.6.2 MONITORING MATERIALS & METHOD

Six 20mm Elster V100 cold water meters were fitted to determine GW volumes produced and RW yield, plus sub-metering of toilet, washing machine, irrigation, GW top-up and garden tap volumes.

A Mercoid Series SBLT2 submersible level sensor was installed in the RW tank to record tank volumes for the purpose of comparing periods of RW availability with RW demands.

APCS WHT290 Watt-hour transducers were installed on the power supply feeding the GW and RW pumps to sample power usage.

All meters and sensors were connected to a multi-channel data logging unit for recoding data on a daily time-step basis.

4.7 RESULTS & ANALYSIS

4.7.1 HOUSEHOLD WATER USE BY SOURCE

Figure 11 compares CS1 household water use by source for the study period with the Perth average, as well as the local suburb average (South Fremantle). The Perth average has been calculated using the same household occupancy rate as the case study site for practical comparison, whereas the local suburb data average is indicative of typical household use in the area. Total MW use for CS1 was 174kL/annum compared to 301kL/annum for the Perth average and 201kL/annum for the local suburb average. The total indoor water use at CS1, of which RW comprised 12% (19kL), was 13% less and 46% higher than the Perth and local suburb averages respectively. External water use at CS1 was comparable to the Perth average and higher than the local suburb average (110 kL/annum compared with 116kL/annum and 91kL/annum), however, its MW use was 72% and 65% less respectively. Instead, the site made use of 13kL/annum and 65kL/annum of RW and GW respectively for external water use. In total CS1 made use of 32kL/annum of RW using a 3.5kL tank with an effective roof catchment of 200m^2.

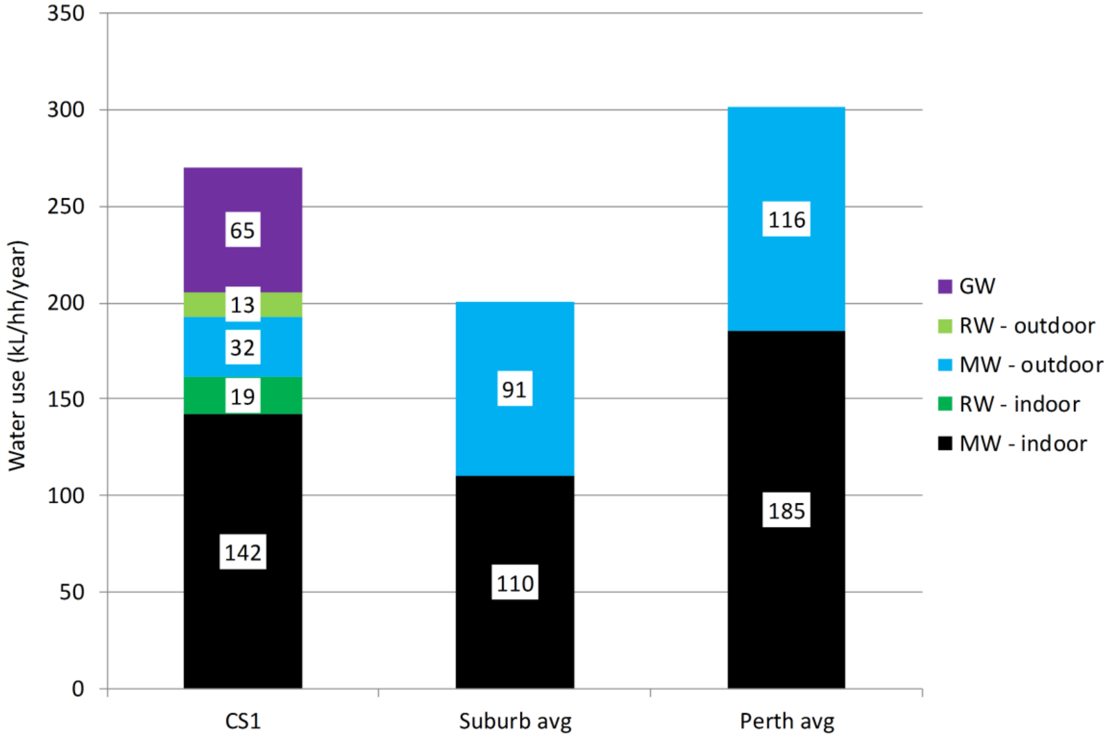


Figure 11: Water use by source for case study 1.

ASSUMPTIONS & QUALIFIERS

The longest period of time when three adults were occupying the house and sharing all the facilities was 54 days (7 October to 30 November 2010). Average daily indoor MW volumes were taken from this period and annualised via simulation. Average daily indoor RW volumes were annualised based on daily indoor non-potable volumes, with the latter also taken from this 54-day period. Lastly, average daily GW volumes were also taken from this period and multiplied by the number of days that the system is operational (refer Section 4.7.2).

Outdoor RW and MW volumes (irrigation and garden tap) are not directly related to occupancy so these volumes were taken from a longer sample period across the seasons as described in Section 4.7.4 and then annualised.

The suburb average water use figures were sourced via the Water Corporation (D. Elletson, personal communication, 21 Jan, 2016). The 58% (indoor use) to 42% (outdoor use) split is based on the 2008/09 Perth Residential Water Use Study (PRWUS) (Water Corporation, 2010).

The Perth average water use figures were extrapolated from data presented in the 2008/09 PRWUS (Water Corporation, 2010), with the indoor water consumption scaled to the number of occupants, but fixing the quantity used for irrigation as this component is unlikely to change regardless of the number of occupants. The PRWUS (2010) states the average annual household water use is 277kL based on 2.6 residents, with 58% used for indoor purposes. This equates to 61.8kL per person per annum for indoor water use and 116kL/annum for outdoor water use. This translates to an indoor water use of 185kL/annum for a three-person household.

4.7.2 GREYWATER VOLUMES – ACTUAL VS MODELLING

Figure 12 expresses the average daily GW volumes of 237L per day recorded at CS1 as an irrigation application rate of 8.8 mm per day over the 27m^2 dispersal area, as well as the modelled projected GW application rate of 6.2mm based on an estimated household GW generation rate of 168L per day, with the additional volumes generated assumed to be due to higher than expected shower use. Running alongside is the monthly water demand of the plants in the GW Hz, assuming a plant crop factor of 0.6 and an irrigation application IEf of 95%. Hydrozone water demand (HzWD) is satisfied year round, compared to the expected deficit of 0.1kL estimated by the modelling, indicating supplementary irrigation is unlikely to be required except during periods when householders are absent.

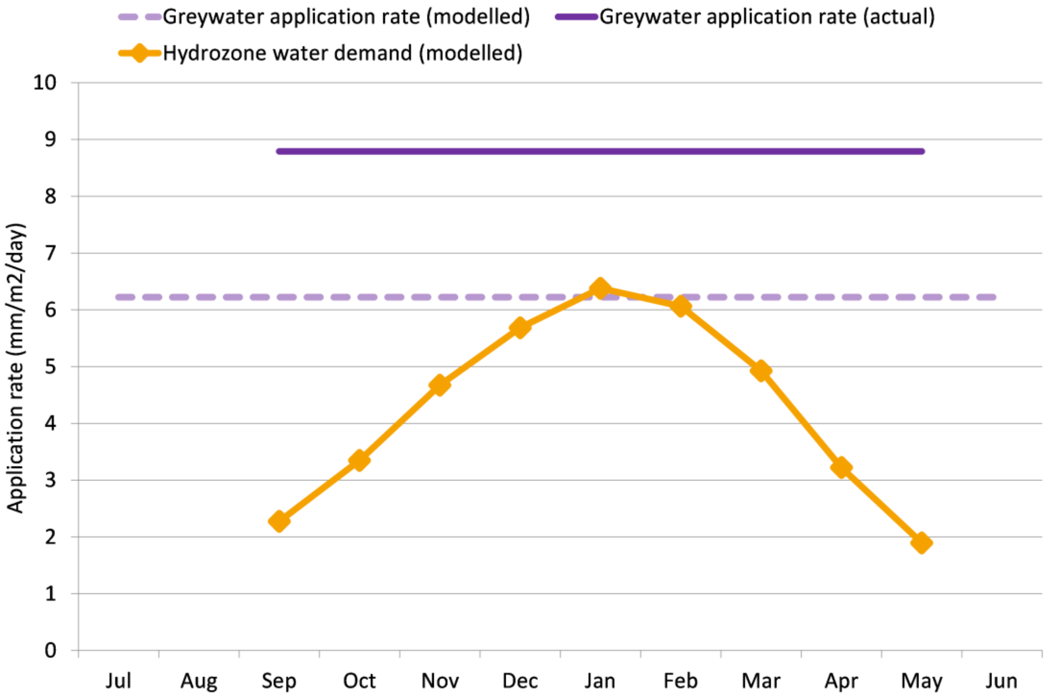


Figure 12: Modelled versus actual greywater volumes generated at the case study 1 expressed as an irrigation application rate (location of Perth, Western Australia).

ASSUMPTIONS & QUALIFIERS

As described in Section 4.7.1, GW volumes were selected from the period of time when three adults were occupying the house. i.e. the 54 days between 7 October and 30 November 2010. The daily average was multiplied by the number of days in the nine-month period of operation (September-May). It is assumed that the system is switched off during the winter months (June-August) when irrigation isn't required.

4.7.3 RAINWATER VOLUMES – ACTUAL VS MODELLING

Table 10 presents the garden water use and inside non-potable water use volumes by source for each month, as well as the proportion of RW or MW consumed.

It can be seen that MW use was 29.6kL for irrigation and 1.8kL for garden tap, totalling 31.4kL, compared with 19.5kL of RW used internally for indoor purposes (toilet and washing machine). This shows that MWNG status was not achieved, as only 62% of MW used outdoors was offset. Likely reasons for this are a combination of over irrigation (refer Section 4.7.4) when MW was in use, combined with lower than anticipated toilet and washing machine use. Table 10 also shows a shortfall in actual RW consumption compared to the modelled consumption of 6.2kL, which may in part be due to lower rainfall experienced during the study period when compared to the 14-year average used in the modelling (refer Figure 13), as well as lower than expected toilet and washing machine usage, reducing yield.

Table 10: Garden and indoor non-potable water use volumes by source for case study 1.

	Irrigation (kL)		**GW top-up (kL)**		**Garden tap (kL)**		**Toilet & washing machine (kL)**	
	RW	MW	RW	MW	RW	MW	RW	MW
July	0.7	0.1	0.0	0.0	0.2	0.0	3.2	0.4
August	0.7	0.1	0.0	0.0	0.2	0.0	3.2	0.4
September	2.3	0.6	0.0	0.0	0.2	0.1	2.9	0.7
October	0.6	2.4	0.0	0.0	0.1	0.2	0.8	2.8
November	0.6	2.3	0.0	0.0	0.1	0.2	0.7	2.8
December	1.1	5.1	0.0	0.0	0.1	0.2	0.8	2.9
January	1.6	4.6	0.0	0.0	0.1	0.2	1.1	2.5
February	0.8	4.7	0.0	0.0	0.0	0.2	0.5	2.8
March	0.0	6.1	0.0	0.0	0.0	0.3	0.0	3.7
April	0.8	2.1	0.0	0.0	0.1	0.2	1.1	2.4
May	1.5	1.4	0.0	0.0	0.1	0.1	2.0	1.7
June	0.7	0.1	0.0	0.0	0.2	0.0	3.1	0.4
Total	11.3	29.6	0.0	0.0	1.3	1.8	19.5	23.6
% Supply	28	72	0	100	41	59	45	55
From Section 4.5.3 **Modelled RW consumption (kL)**					*From table above* **Actual RW consumption (kL)**			
38.3					32.1			

Also of note is that the results show that MW was still used during periods when RW was available in the tank due to a mixing or ‘shandying’ of the two sources by the mains water backup valve (MWBV). Product literature indicates that a small amount of MW can be used during operation of some MWBV devices based on the system design, however volumes or percentages are not explicitly given. The results indicate that the MWBV had an average system inefficiency of 12% across the monitoring period, with approximately 20 litres per day of mains water used, compared to 123 litres per day of rainwater used.

Figure 13 presents the local rainfall during the study period (641mm) with the recent average of 709mm (1996–2010) used for the modelling by month. The average monthly rainfall during the study period was lower than the modelled average for eight months of the year. Importantly, these ‘lower than average’ rainfall months in spring and autumn are when reduced rain has most impact on tank yield, especially with small tanks. The higher than average months of June and July are of little consequence as small tanks with adequate catchments are typically full and overflowing.

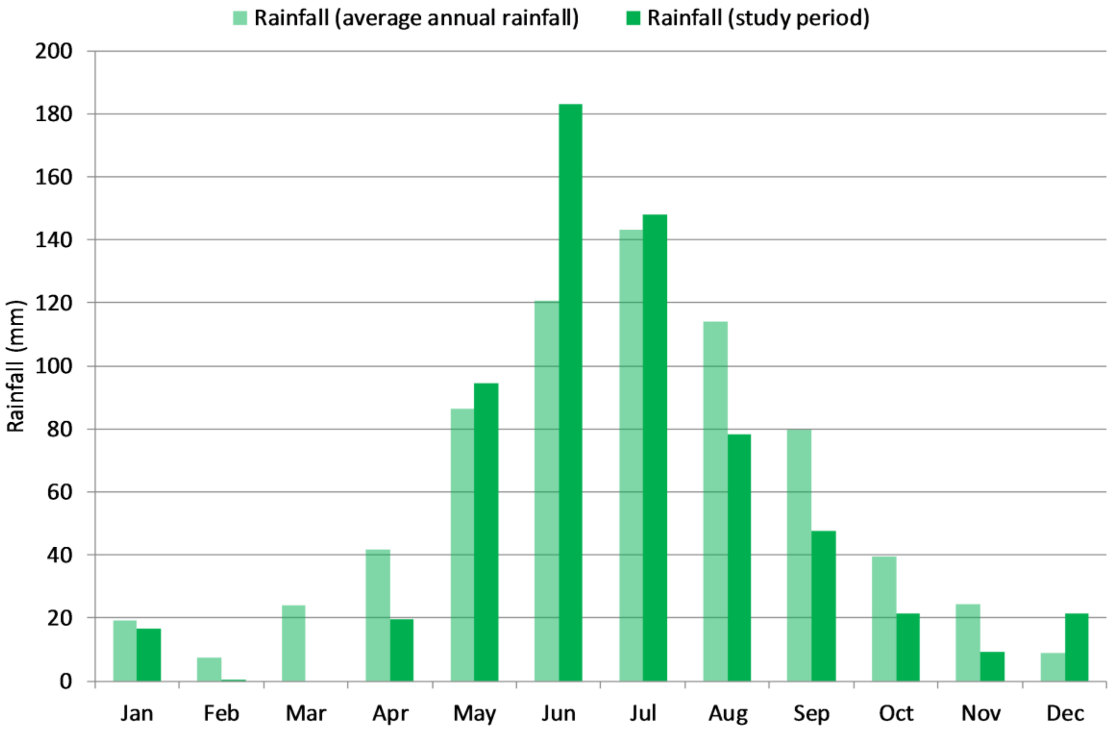


Figure 13: Comparison of rainfall during study period (2010–2011) and recent average (1996–2010) for case study 1 (using data from Bureau of Meteorology Station 009215).

ASSUMPTIONS & QUALIFIERS

The amount of RW used during the year of the study period was also affected by the variation in household occupancy. In an attempt to best determine the likely volumes of the house under full occupancy over the monitoring period, the volume of RW available in the tank (as indicated by the tank level sensor) was matched with the average water use for streams that used RW (i.e. washing machine, toilet, irrigation and backyard taps) then extrapolated over the year.

The amount of RW available in the tank at 9am was calculated each day by subtracting toilet, washing machine, backyard taps and irrigation use during the previous day from the tank volume at 9am the previous day. If the tank ran out during the day, RW was allocated to the different streams in the following order: toilet, washing machine, backyard taps and irrigation, until all RW had been used. After this, MW was allocated to the stream.

These RW volumes used also took into account inefficiency in the operation of the MWBV, that is, each time RW was drawn, some MW was also used. The MWBV inefficiency (i.e. percentage of MW used when RW was available) was calculated by dividing the MW used (litres per day) by the total amount of water used that day (i.e. MW

+ RW). The average percentage of MW used was then calculated, indicating an average inefficiency of 12% that is, approximately 20L per day of MW was used when RW was available, with an average RW use of 123L per day.

The rainfall data presented in Figure 13 was sourced from the Bureau of Meteorology station in Swanbourne.

4.7.4 IRRIGATION VOLUMES – ACTUAL VS MODELLING

Figure 14 presents the modelled irrigation demand, excluding GW Hz, compared against actual irrigation volumes. The graph indicates the actual irrigation volumes applied exceeds the modelled estimations for all months, with 21.9kL/annum being modelled and 40.1kL/annum applied. RW, which comprises 28% (11.3kL) of the applied irrigation, is used more than MW only during the rainy winter months. Of note is that March was the only month where no RW was available.

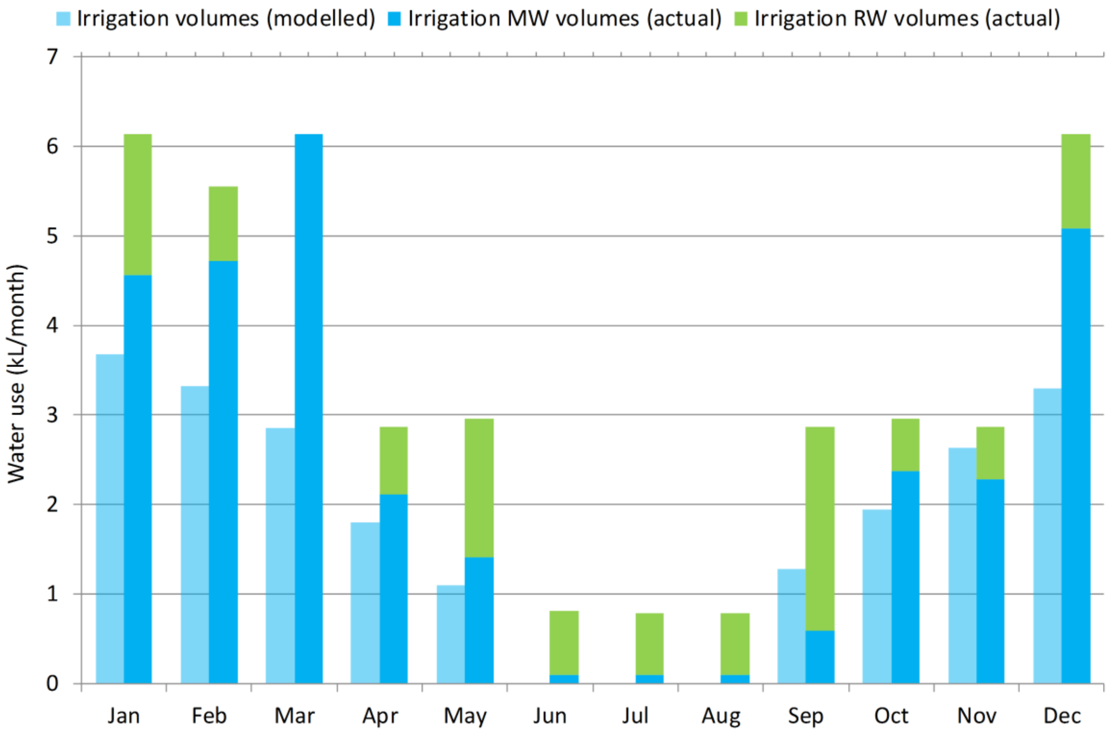


Figure 14: Comparison of modelled irrigation demand versus actual usage for case study 1.

The reason for over irrigation is due to a combination of poor operation of scheduling, combined with unnecessary hand watering, brought about by a combination of equipment challenges and operational management. These are discussed further in Section 4.8.

ASSUMPTIONS & QUALIFIERS

Irrigation volumes were established by sampling daily metered data across the seasons (summer, winter and autumn/spring).

The proportion of RW and MW contributing to irrigation was determined on the grounds of RW being available in the tank to service the demand as described above in Section 4.7.3 *Assumptions & Qualifiers*.

4.7.5 ENERGY INTENSITY OF WATER SOURCES

Monitoring of the electricity usage of the GW system and the RW system indicated an energy intensity of around 0.5kWh/kL of GW supplied and 2.5 kWh/kL of RW supplied. The greater efficiency of the GW in terms of water volume supplied per unit of energy expended is due to the difference in pump operation between the two systems. The GW pump is switched on in response to the pump out tank filling up and then switching off until the tank refills again, typically one to two days later. Conversely the RW pump switches on and off according to demand from any fixtures or appliances connected to it, resulting in multiple pump start-ups, which consumes additional power.

ASSUMPTIONS & QUALIFIERS

The GW system power consumption data was established over a six-month period and the meter was consistently reliable. The RW meter however was consistently faulty, with the exception of a one-week period early in the monitoring period. RW was in use during this period in typical volumes, so the sample can still be considered useful as an indication of typical energy intensity of supply.

4.8 REFLECTIONS & LESSONS LEARNED

4.8.1 WATER SYSTEM EQUIPMENT PERFORMANCE

GREYWATER SYSTEM

The GW system performed well throughout the monitoring period, with no malfunction events recorded, however GW volumes were significantly higher than anticipated. During periods of full occupancy, GW volumes often exceeded the estimated Hz water demand, although the application rates were still within the specified loading infiltration rate (LIR) for sandy soils (Department of Health, 2005).

As flagged in Section 4.8.2, high water use in the shower is the likely cause for the greater than expected GW volumes. Whilst this does not directly impact on the MWNG model per se, the over application of greywater increases the possibility of detrimental impact on soil (Gross *et al.*, 2005; Gross *et al.*, 2008) and increases the likelihood of nutrient leaching (Mohamed *et al.*, 2013) so should be avoided. In this instance, given the volumes are within the specified LIR and provided GW appropriate products are used (Toifl *et al*., 2015) the risk can be assumed to be minimal.

A limitation of direct diversion–type GW systems is that they typically discharge greywater as generated (or when the temporary storage tank is full in the case of this system) so over application is a risk. This is best managed through occupant behaviour, through the timing of showers and staging of washing loads to roughly match generation with Hz demand so as to prevent under watering or over overloading. This assumes a certain level of understanding of how the system operates, plus engagement by household occupants in order to achieve an optimal outcome.

RAINWATER SYSTEM

Overall, the RW system worked well during the monitoring period, with no major equipment failures, however, as identified in Section 4.8.3, MW was still being used by the streams being serviced by RW due to ‘shandying’. The average figure of 12% applied to the extrapolated MW data for the toilet, washing machine and garden use when RW was available, had a significant impact on the MWNG outcome. Whilst the manufacturer of the MWBV confirmed that some shandying between RW and MW commonly occurs with the unit (*Davey Rainbank*), information on the extent and variation of mixing was not readily available. Future projects would have to either select a MWBV device that provided a positive switchover between sources, or factor in an assumed ‘inefficiency factor’ to account for the shandying.

IRRIGATION SYSTEM

Irrigation volumes during the monitoring period were higher than anticipated, and this has been identified as the main reason MWNG was not achieved. This can be attributed to several interrelated factors leading to poor scheduling practices.

Firstly, having the irrigation system being supplied by two sources (RW and MW) led to complications when sources switched. The RW system supplied water at greater pressure (approximately 200kPa) than the MW supply (around 140kPa). This meant that a greater volume of RW was applied compared to MW for the same time period. The automatic switching between the two sources (based on RW availability) would make it difficult to adjust the scheduling to account for this variation. The use of an adjustable pressure regulating valve to set the maximum operating pressure regardless of supply, or the use of pressure compensating irrigation emitters (where suitable), could be used to address this issue in future projects.

Secondly, the performance of the soil moisture sensor was unreliable, often preventing irrigation from occurring when it was necessary, or switching it off part way through. As a new capacitance-type soil moisture sensor product on the market (at the time of the project) it was included to see if it would help prevent unnecessary irrigation, however its poor performance was in keeping with the trial of a similar low-cost domestic market sensor by the author as part of previous research (Byrne *et al*., 2002). Consideration should be given to other devices that can help to reduce unnecessary irrigation, such as evapotranspiration sensors and rain shut-off switches, and these are discussed further in the following case study chapters.

Finally, decisions to increase run times and/or hand water by the occupants resulted in higher than forecasted irrigation volumes being applied, which were likely triggered to some extent by the source supply variation and poor sensor performance.

4.8.2 MONITORING METHODOLOGY & RELIABILITY OF DATA

In principle, the data collection methodology deployed at CS1 based on flow meters to record the water volumes from the various sources (GW, RW and MW) and the relevant demands (toilet, washing machine, irrigation and garden tap) should have been adequate to determine whether MWNG gardening had been achieved, as well as to verify the accuracy of the assumptions used in the design modelling.

In practice, the variation in household occupancy throughout the monitoring period meant that sampling periods had to be used to establish average volumes for extrapolation, combined with the use of a RW tank level sensor to determine whether the toilet, washing machine, irrigation and garden tap demands would be met by RW or MW through simulation. Whilst sound in approach, the robustness of the data set is clearly affected.

The evaluation of the MWNG model via CS1 was further compounded by the impact of the inefficiency of the MWBV on RW yield and operational issues with the irrigation system resulting from pressure variations (automatic source switching between RW and MW), the unreliability of the soil moisture sensor and poor scheduling leading to overwatering.

4.8.3 ALTERNATIVE WATER SYSTEM COSTS & PAYBACK PERIODS

GREYWATER SYSTEM

Table 11 presents the supply, installation and operational costs for the GW system at CS1. The cost build-up is shown by item, along with the estimated life span / replacement intervals and annualised costs. The total cost over life of the system is estimated to be \$9,682, assuming an operational life of 20 years (Memon *et al*., 2005). This equates to \$484 per year when annualised over this period, or \$7.45 per kL based on the 65kL of GW supplied by the system. Using a figure of \$1.82 per kL[1] for MW suggests a payback period of 82 years, which is well beyond the assumed 20-year life span of the system. The system operating costs including electricity, plus annualised pump replacement and tank desludging is approximately \$214 per annum.

Table 11: Greywater system costs for case study 1.

Greywater system items	**Capital cost (\$)**	**Estimated life/ replacement intervals (Yrs)**	**Annualised cost (\$)**	**Life of system costs (\$)**	**NPV (\$)** Discount rate: 7%
GW system - supply and install + hired labour for plumbing modifications	5500	20	275	5500	5500
GW pump replacement	800	7.5	107	2133	1572
Maintenance by user	0	NA	0	0	0
Desludge pump tank	220	5	44	880	568
Desludge primary tank	500	10	50	1000	754
Power per annum (0.5kWhr/kL) @ \$0.26/kWhr[2] *Annual Operating cost*	0	20	8	169	85
GW system - cost over life	7020	20	484	9682	8479

[1]The unit cost of water is based on local supply charges for MW taking into account the tariff tiers relative to the total property water consumption (Water Corporation, 2016).

[2]Local supply flat tariff rate (Synergy, 2016).

The GW system costs are for the supply and install of the GDD only, plus all associated plumbing and electrical works, but does not include the dripline irrigation component as this cost would be normally be covered in a typical BAU irrigation installation (which is around \$10/m^2 for dripline).

The cost of the GW system installation is at the upper end of the GDD range (ATA, 2009), largely due to the requirement for excavation for the tanks and the complexity of the install. The installation process also has the potential to be highly disruptive and is only possible when access for excavation equipment is available. The basis for choosing this system despite these factors, was the expectation reduced filter cleaning (and clogging) resulting from the inclusion of a settlement tank. It was the experience of the author that filter clogging was a common occurrence with GDD's which would lead to poor system performance, and this is supported by other local studies (Evans *et al*., 2009). The filter was inspected several times during the monitoring period, with no evidence of clogging, indicating that the settlement tank was performing as expected, resulting in reduced maintenance and reliable performance.

RAINWATER SYSTEM

Table 12 presents the supply, installation and operational costs for the RW system at CS1. The cost build-up is shown by item, along with the estimated life span / replacement intervals and annualised costs. The total cost over life of the system is estimated to be \$10,416 assuming an operational life of 20 years (Gurung *et al*., 2012). This equates to \$521 per year when annualised over this period, or \$16.33/kL based on the 32kL of RW supplied by the system. Using the figure of \$1.82 per kL for MW suggests a payback period of 179 years, which is well beyond the assumed 20-year life span of the system. The system operating costs including electricity, plus annualised pump and MWBV replacement is approximately \$121 per annum.

Table 12: Rainwater system costs for case study 1.

Rainwater system items	**Capital cost ($)**	**Estimated life/ replacement intervals (Yrs)**	**Annualised cost ($)**	**Life of system costs ($)**	**NPV ($)** Discount rate: 7%
RW system - tank, pump, MWBV, soakwell	6500	20	325	6500	6500
Hired labour for plumbing to supply to toilet, washing machine, and irrigation	1500	20	75	1500	1500
RW pump replacement	500	10	50	1000	754
MWBV replacement	500	10	50	1000	754
Maintenance (by user)	0	NA	0	0	0
Power per annum (2.5kWhr/kL) @ $0.26/kWhr Operating cost	21	20	21	416	220
RW system - cost over life	9021	20	521	10,416	9729

The RW system costs are for the tank, pump, MWBV and associated roof drainage and RW supply plumbing modifications; they do not include original roof guttering costs as these were already in place and are also required in a BAU roof drainage scenario.

The supply and installation costs of a RW tank at CS1 are higher than those referenced in the literature for a similar-sized system, such as Coombes *et al.* (2003) and Gurung *et al.* (2012), which can be attributed to the in-ground installation, which required a specialist tank and excavation works. In this application, in-ground installation was favoured despite the additional expense due to the small size of the garden and the preference to utilise the available space for landscaping.

The limitations of using a payback model based on MW cost per kilolitre savings is discussed in Chapter 7 (Discussion) and Chapter 8 (Conclusion).

INTENTIONALLY BLANK PAGE

CHAPTER 5: CASE STUDY 2

5.1 CHAPTER INTRODUCTION

This chapter covers the second of three case study gardens (CS2) that were designed and built by the author as part of this study based on the Sustainable Urban Gardening (SUG) and Mains Water Neutral Gardening (MWNG) concepts. The chapter begins with an overview of CS2 (Section 5.2) followed by a description of the landscape design and key SUG attributes (Section 5.3).

Section 5.4 describes the water system infrastructure installed, including greywater (GW), rainwater (RW) and irrigation systems. Section 5.5 presents the water balance modelling underpinning the MWNG landscape design, including estimated GW volumes, garden water requirement and RW yield, as well as the projected MWNG outcome.

Section 5.6 describes the water usage monitoring undertaken post garden establishment, including equipment and techniques used. The results and analysis of the findings are described in Section 5.7 and details on lessons learned from this case study are provided in Section 5.8. Further discussion is provided in Chapter 7 (Discussion), along with the other two case studies for comparison.

5.2 CASE STUDY OVERVIEW

CS2 is a three bedroom, one bathroom, detached dwelling located on a 600m^2 block in the Perth suburb of White Gum Valley, Western Australia, where the local climate type is classified as Mediterranean (Bureau of Meteorology, 2015) and the soil type is coarse sand, typical of the Karrakatta soil association of the Spearwood dune system of that area (McArthur, 2004).

The house was built in the mid-1960s, but had undergone basic renovations around 2009/10 which included the installation of BCA-compliant, WELS-rated, water-efficient plumbing fixtures. Originally the property had been serviced solely by mains water (MW) to supply all internal and external demands, and mains sewer for wastewater disposal. The arrangement of the existing plumbing allowed for access to bathroom and laundry GW sources for diversion and reuse, plus connection of a RW supply to the existing toilet, washing machine and garden tap. More information on the equipment installed at CS2 is provided in Section 5.4 (Water System Infrastructure).

As a three-bedroom house, occupancy included three persons during the study period (the author and family). The occupants included the author and an adult female, both in the 31–40 year age group, and one child aged under two years.

5.3 LANDSCAPE DESIGN

5.3.1 DESIGN INTENT & PROJECT INSIGHTS

The brief for the landscape design (established between the author and property owners) was to create a cost-effective garden suited to a young family. A functional outdoor living space was to be created in the backyard using the existing pergola structure, and an old cubby house retained and restored. Consideration was to be given to improving the thermal performance of the house given its poor orientation and exposed glazing to morning and afternoon sun. Existing mature native species in both the front and backyards were to be retained (including established eucalypt species on the northern side that created heavy shade). Food production, biodiversity and water efficiency initiatives were also to be addressed in line with the author's SUG framework.

From the inception, this project was to be delivered on a modest budget as the owners only ever intended it to be a rental, and whilst supportive of the author's intent to develop the garden, capital expenditure was to be minimised. Instead the author focused on reuse of materials and simple landscape construction methods.

The GW and RW system were to be simplified from CS1, including above-ground RW storage and a new (at time of construction) comparatively lower cost GW diversion unit. Irrigated garden areas would be minimised to keep costs down (and to keep within the MWNG water budget), and dryland native planting used for the majority of landscape area.

5.3.2 SUSTAINABLE URBAN GARDENING FRAMEWORK AND DESIGN RESPONSE

Table 13 provides a summary of the key landscape design elements and supporting gardening activities at CS2 in response to the SUG framework developed by the author. The landscape design prepared for the property is presented as Figure 15. Where relevant, an alphanumeric reference has been listed alongside the landscape design elements in the table correlating to their location on the landscape plan. Photographs are provided in Figure 16 for further context and detail, using the same reference key.

Table 13: Summary of the sustainable landscape design elements and supporting gardening activities for the case study 2.

SUSTAINABILITY GOAL 1: ENERGY EFFICIENCY	
Desired Outcomes	**Design Elements & Gardening Activities**
Reduced fossil fuel use from embedded energy in materials and in the operations of the house and garden.	Shading devices installed to exposed eastern and western facing windows (1A). Extensive plantings to reduce heat loading surrounding house (1B). Repurposed materials used where possible including timber, paving and aggregates (1C).
SUSTAINABILITY GOAL 2: ORGANIC WASTE RECYCLING & SOIL MANAGEMENT	
Desired Outcomes	**Design Elements & Gardening Activities**
Local soil carbon regeneration and nutrient recycling.	Composting bins and worm farm to recycle house and garden organic waste (2A). Soil conditioning and mulching to increase soil carbon and naturally improve soils over time (2B).
SUSTAINABILITY GOAL 3: BIODIVERSITY & HABITAT RESTORATION	
Desired Outcomes	**Design Elements & Gardening Activities**
Enabling indigenous plant, insect and animal life to thrive.	Considered plantings (native and exotic) to provide food source for insects and birds (3A). Micro bat roosting box (3B). Damp-land habitat feature (3C). Rubble wall for insect and reptile refuge (3D). Timber posts for insect and reptile refuge (3E). Deep mulching and leaf litter accumulation to encourage invertebrate populations and bird foraging (3F).
SUSTAINABILITY GOAL 4: ORGANIC PEST & DISEASE MANAGEMENT	
Desired Outcomes	**Design Elements & Gardening Activities**
Achieving natural ecosystem functioning that controls pests and weeds without toxic chemical use.	Companion planting to encourage predatory insects and pest distraction (4A). Design allows for effective deployment of cultural practices for organic pest and weed control (4B).

SUSTAINABILITY GOAL 5: LOCAL FOOD PRODUCTION	
Desired Outcomes	**Design Elements & Gardening Activities**
Local food production contributing to household food supply.	Space allocated for intensive vegetable growing (5A). Fruit trees in garden bed and pots (5B). Fruiting vines on trellis (5C). Diverse range of edible herbs in garden beds and pots (5D).
SUSTAINABILITY GOAL 6: WATER CONSERVATION	
Desired Outcomes	**Design Elements & Gardening Activities**
Reducing water-based ecological footprint.	Hydrozing for irrigation management (refer Figure 17). Efficient irrigation system (6A). GW applied to appropriate hydrozone (Hz) (6B). RW harvesting for non-potable indoor uses to offset MW use for irrigation (6C). Water efficient gardening practices deployed including soil building, mulching and plant selection/care (refer Appendix 1).
SUSTAINABILITY GOAL 7: HEALTH AND WELLBEING OF HOUSEHOLDERS	
Desired Outcomes	**Design Elements & Gardening Activities**
Achieving a liveable housing habitat including daily contact with nature.	Landscaping enhances thermal performance for house, increasing occupant comfort (7A). High quality outdoor living areas providing regular contact with garden (7B). Extensive native habitat garden providing regular contact with nature (7C). Engaging outdoor play features for children (7D). Fresh food available from the garden (7E).

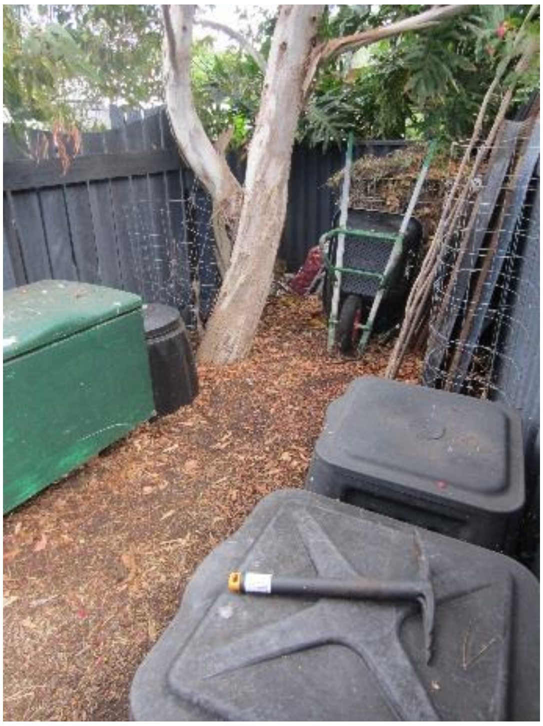
Figure 15: Landscape plan for case study site 2.

Figure 16: Photographs of case study site 2 (photo credits: M. Ward; R. Frith; J. Byrne).

1A: Shading devices installed to exposed eastern and western facing windows.

1B: Extensive plantings to reduce heat loading surrounding the house.

1C: Repurposed materials used where possible including timber, paving and aggregates.



2A: Composting bins and worm farm to recycle house and garden organic waste.

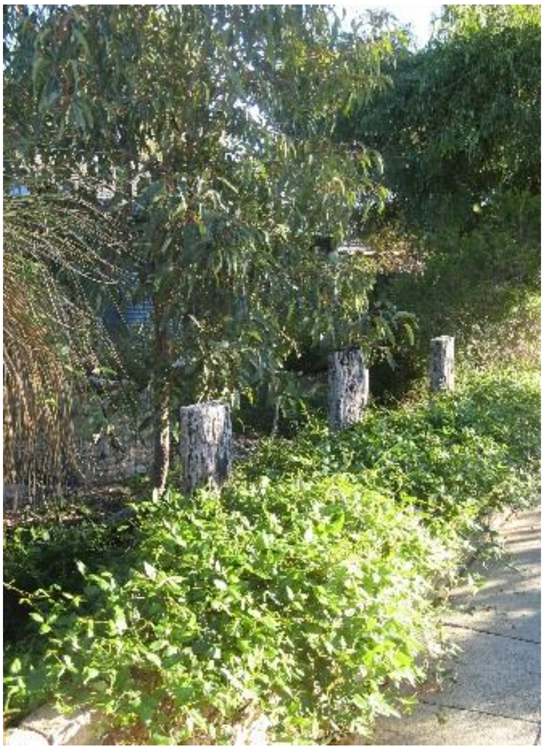
2B: Soil conditioning and mulching to increase soil carbon and naturally improve soils.

3A: Considered plantings to provide food source for insects and birds.

3B: Micro bat roosting box.

3C: Damp-land habitat feature.

3D: Rubble wall for insect and reptile refuge.



3E: Timber posts for insect and reptile refuge.

3F: Deep mulching and leaf litter accumulation to encourage invertebrate populations and bird foraging.

4A: Companion planting to encourage predatory insects and pest distraction.

4B: Design allows for effective deployment of cultural practices for organic pest and weed control.

5A: Space allocated for intensive vegetable growing.

5B: Fruit trees in garden bed and pots.

5C: Fruiting vines on trellis.

5D: Diverse range of edible herbs in garden beds and pots.

6A(i): Irrigation system – valve manifold.

6A(ii): Irrigation system – controller.

6A(iii): Irrigation system – evapotranspiration sensor.

6A(iv): Irrigation system – dripline.

6A(v): Irrigation system – pot sprays.

6B(i): Greywater system – dripline.

6B(ii): Greywater system – collection sumps, pump and blower.

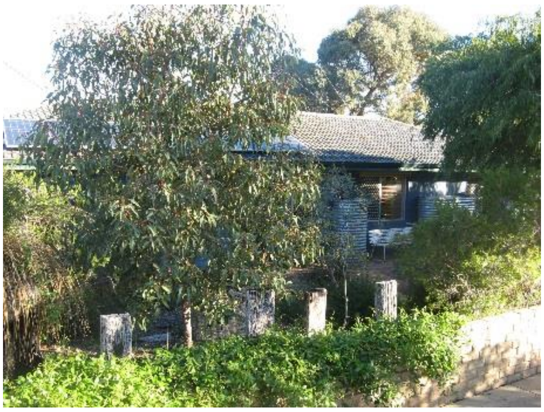
6C(i): Rainwater system – tank.

6C(ii): Rainwater system – rain heads with leaf screen.

6C(iii): Rainwater system – pump and mains water backup valve.

7A: Landscaping enhances thermal performance of the house, increasing occupant comfort.

7B: High quality outdoor living areas providing regular contact with the garden.



7C: Extensive native habitat garden providing regular contact with nature.

7D: Engaging outdoor play features for children.

7E: Fresh food available from the garden.

5.4 WATER SYSTEM INFRASTRUCTURE

5.4.1 GREYWATER REUSE SYSTEM

The GW reuse system at CS2 was a proprietary greywater diversion device (GDD) known as the GreyFlow PS-PP by Advanced Wastewater Systems (WA Department of Health approval number WMKT 21323), which was installed as per the WA Department of Health *Code of Practice for the Reuse of GW in Western Australia* (Department of Health, 2010).

The GDD collected GW via two interceptor traps containing porous spun polyethylene pads to provide coarse filtration prior to filling a 30L sump which housed a submersible pump operated by a level switch. When the pump out trigger point was reached, GW was discharged to designated garden areas via dripline irrigation in accordance with Department of Health (2010) guidelines. In the event of pump failure or filter blockage, the system would direct GW to sewer.

The GreyFlow PS-PP also included an automated filter backflush system. At nominated pump cycles, air from a blower was directed through the filter pads to dislodge clogging material. Whilst the blower was operating, the submersible pump discontinued so that GW flowing across the filter pads scours dislodged material from the pads and took it to sewer.

Photographs of the key features and general arrangement of the GW system installed at the CS2 are shown in Figure 16, photos 6B(i)–6B(ii) (page 83).

5.4.2 RAINWATER HARVESTING SYSTEM

The RW harvesting system at CS2 was installed in accordance with *AS/NZS 3500 Plumbing and Drainage – Water Services* (Standards Australia, 2003), and the *Rainwater Tank Design and Installation Handbook* (National Water Commission, 2008a).

Rain was collected off 70m^2 of roof catchment via a standard roof guttering and ‘dry-feed’ gravity drained pipework arrangement, with the catchment area being limited to this size by practical roof plumbing considerations. Leaf traps were located on all gutter outlets to prevent debris from entering the tank and a first flush device with manual drain valve installed prior to water entering the tank.

RW was stored in a 2,500L above-ground corrugated steel RW tank, with the overflow diverted to a soak well. A pressure switch activated pump was connected to the tank.

Pressurised RW was supplied to the end-use fixtures and appliances (toilet, washing machine and garden tap) via a MW backup valve which supplied RW on demand (when available), and supplied MW as back-up.

Photographs of the key features and general arrangement of the RW harvesting system installed at CS2 are presented in Figure 16, photos 6C(i)–6C(iii) (page 83 – 84).

5.4.3 LANDSCAPE HYDROZONES & IRRIGATION SYSTEM

The landscape design at CS2 was based on five Hzs as identified in Figure 17, with size and location of the various Hzs being determined by the designer's response to available water, and prioritisation of gardening activities in line with the SUG framework.

The GW Hz (Hz1) received water from the GW system which discharged as generated once the pump level switch was triggered as described in Section 5.4.1. Plant selection included a range of species suited to untreated GW (Department of Health, 2010). The other Hzs included Vegetables and Herbs Hz (Hz2); Lawn Hz (Hz3); Pots Hz (Hz4); and Native (Dryland) Hz (Hz5), which was unirrigated.

The timing of watering to Hz2, Hz3 and Hz4 was automated via a typical programmable multi-station irrigation controller fitted with an evapotranspiration sensor to reduce unnecessary irrigation during mild weather or rain events. The controller was also used to operate a dedicated GW 'top-up' line to supply MW to Hz1 during periods when the house was unoccupied and irrigation was required, or when GW volumes were inadequate to meet plant water demand. The top-up entry point was via a sink trap, as described for CS1.

The design and installation of the irrigation system was undertaken in accordance with relevant irrigating industry standards (Cape, 2006; IA, 2012).

Photographs of the key features and general arrangement of the irrigation system installed at CS2 are shown in Figure 16, photos 6A(i)–6A(v) (page 82 – 83).

Figure 17: Hydrozone plan for the case study 2.

5.4.4 WATER SYSTEM INTEGRATION

Figure 18 shows the integration of the MW, GW and RW supplies, including water flows from source to sink. MW is the sole service supplying the internal potable demands, including kitchen taps and dishwasher, bathroom taps and shower/bath, and laundry taps. MW also supplies the irrigation demand for Hz2, Hz3 and Hz4, plus the top-up line to the GW system. RW supplies internal non-potable demands, including toilet and washing machine, plus the garden tap. If RW is unavailable, then these demands will be met by MW via the MW backup valve. GW generated from the bathroom (hand basin and shower/bath) and laundry (laundry basin and washing machine) is applied to Hz1.

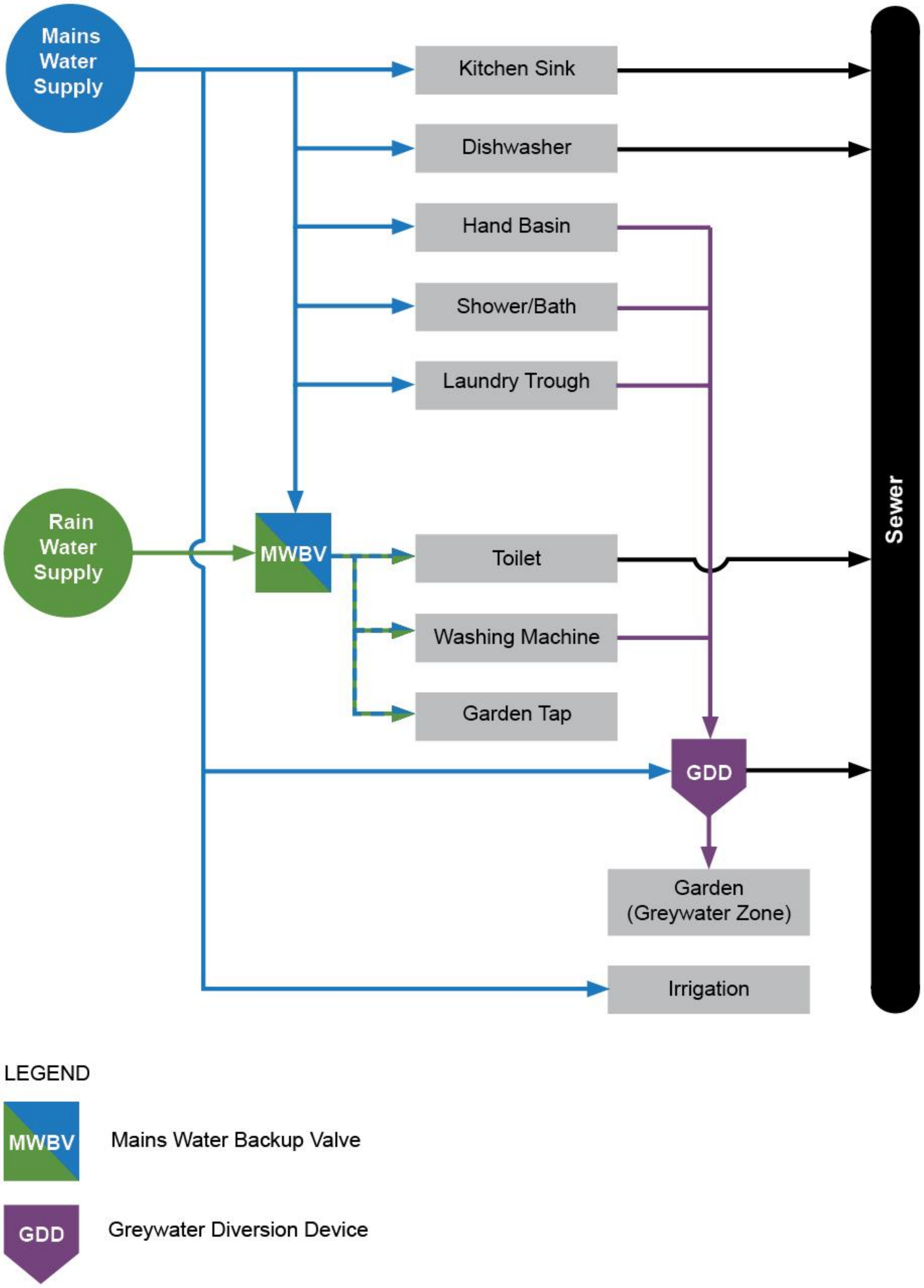


Figure 18: Water system design schematic illustrating the integration of the various water sources at the case study 2, including water flows from source to sink.

5.5 WATER BALANCE MODELLING

The following section outlines the water balance modelling for the CS2 undertaken at the design phase using a tailored spreadsheet tool developed by Hunt *et al.* (2011b). The modelling included estimation of GW volumes, irrigation demand and RW yield based on the MWNG objective.

5.5.1 GREYWATER VOLUMES

Table 14 presents the Department of Health (2010) estimated daily GW generation volumes, as well as what is likely to be generated using water-efficient fixtures assuming a 49% reduction in laundry GW by replacing top-loading washing machines with front loaders (Patterson, 2004), and a 35% reduction in bathroom GW by installing water-efficient shower and tap fixtures (from 14L to 9L per minute and 9L to 6L per minute respectively) (Byrne *et al*., 2008).

Table 14: Regulatory greywater design volumes compared to estimated rates for the case study 2.

GW source	Design volumes* (L/person/day)	Water efficient volumes (L/person/day)	Water efficient volumes (L/house/day = 3 People)
Bathroom	60	39	117
Laundry	40	22	66
Total	100	61	183

*Source: Department of Health (2010)

Figure 19 shows the estimated daily household generation of GW (183L per day) as providing an irrigation application rate of 4.6mm per day over the 40m^2 area. Running alongside is the Hz water demand, assuming a plant crop factor of 0.6 for mixed perennial species including hardy fruit trees and vines and an assortment of perennial understorey shrubs, grasses and groundcovers. The Hz water demand also considers an irrigation application inefficiency (IEf) of 95%. It can be seen that during the months of November to February there is insufficient water to meet the irrigation demand and so additional 5.9kL will need to be provided as ‘GW top-up’.

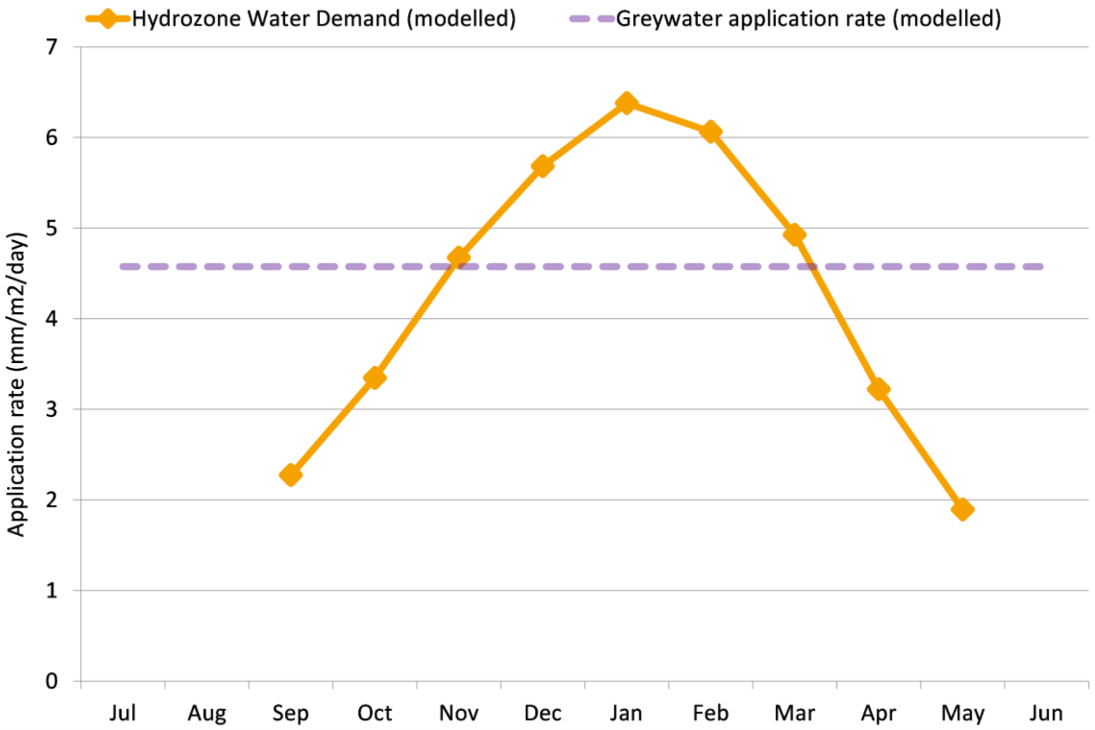


Figure 19: Estimated greywater application rates compared with estimated hydrozone water demand for case study 2 (location of Perth, Western Australia).

5.5.2 IRRIGATION DEMAND

Irrigation volumes for the three Hzs serviced by MW (Hz2, Hz3, Hz4) via the programmable irrigation system were calculated for the purposes of estimating garden water demand, noting that there are no volumes provided for Hz5 as it was unirrigated. Table 15 outlines the key information used in the modelling for each Hz.

Table 15: Irrigation modelling inputs for case study 2.

Parameter	**Hz1 Mixed Perennials (GW)**	**Hz2 Vegetables & Herbs**	**Hz3 Lawn**	**Hz4 Pots**	**Hz5 Natives (Dryland)**
Area (m^2)	40	4	10	2	284
Crop factor	0.6	0.8	0.5	0.8	NA
Root depth (m)	0.50	0.30	0.30	0.30	NA
Canopy cover (%)	100	100	100	0	NA
Irrigated by:	GW	MW	MW	MW	Not Irrigated
Then by:	MW	MW	MW	MW	NA

Table 16 presents estimated monthly irrigation demand for each Hz based on local evapotranspiration rates.

Table 16: Estimated irrigation demand by hydrozone (kL) for case study 2.

Month	Evapo-trans. Rate* (mm/day)	Hz1 Mixed Perennials (GW)	Hz2 Vegetables & Herbs	Hz3 Lawn	Hz4 Pots	Hz5 Natives (Dryland)	Total (kL/month)
January	10.1	7.91	1.05	1.65	0.56	0.00	11.7
February	9.6	7.03	0.94	1.47	0.50	0.00	9.93
March	7.8	6.11	0.81	1.27	0.43	0.00	8.63
April	5.1	3.87	0.52	0.81	0.27	0.00	5.46
May	3	2.35	0.31	0.49	0.17	0.00	3.32
June	2.2	0.00	0.00	0.00	0.00	0.00	0.00
July	2.1	0.00	0.00	0.00	0.00	0.00	0.00
August	2.6	0.00	0.00	0.00	0.00	0.00	0.00
September	3.6	2.73	0.36	0.57	0.19	0.00	3.85
October	5.3	4.15	0.55	0.86	0.29	0.00	5.86
November	7.4	5.61	0.75	1.17	0.40	0.00	7.92
December	9	7.05	0.94	1.47	0.50	0.00	9.95
Total (kL/year)	–	46.80	6.24	9.75	3.30	0.00	66.09

*Bureau of Meteorology Station 009215.

5.5.3 RAINWATER VOLUMES

RW harvesting modelling was performed using average daily rainfall data taken from the nearest Bureau of Meteorology weather station to ascertain likely RW yields (given the available roof catchment area and practical tank sizing considerations) based on the following system design parameters:

- RW to supply toilet, washing machine and garden tap, with automatic MW back-up.
- The minimum tank size is determined by the volume of RW that can be effectively used to that this volume will offset the equivalent amount of MW used for garden meet toilet and washing machine demand during wet periods, to the extent irrigation during dry periods, effectively making it ‘MW neutral’.

The modelling inputs and internal water demands are presented in Table 17.

Table 17: Rainwater harvesting modelling outputs for case study 2, using daily time-step, supply-demand side modelling (Hunt *et al.*, 2011b).

Rainfall modelling inputs	
Catchment area (m^2)	70
Catchment efficiency (%)	80
Loss to adsorption (mm/event)	0.2
Occupancy rate	3
Toilet demand (L/p/d)	27
Washing machine demand (L/p/d)	22

Table 18 presents the modelling results, including estimated RW used under the different tank size scenarios noting there is limited increase in yield return relative to increasing the tank size, as well as reliability (percentage of time that water is available to meet demand) and satisfaction (proportion of demand met).

Table 18: Rainwater harvesting modelling outputs for case study 2.

Rainfall modelling outputs	**Tank volume (kL)**				
	2.5	**3.5**	**5**	**7.5**	**10**
Total water available (kL/year)	49.4	49.4	49.4	49.4	49.4
Annual Overflow (kL/year)	10.2	8.8	7.2	4.8	2.9
Efficiency + adsorption loss (kL/year)	11.1	11.1	11.1	11.1	11.1
Average Rainfall (mm/year)	706.2	706.2	706.2	706.2	706.2
Total demand (kL/year)	53.7	53.7	53.7	53.7	53.7
Reliability (% time)	50%	53%	56%	61%	64%
Satisfaction (% volume)	52%	55%	58%	62%	66%
RW used (kL/year)	**28.1**	**29.5**	**31.1**	**33.5**	**35.4**

5.5.4 MAINS WATER NEUTRAL BALANCE

Table 19 compares the internal demand (toilet and washing machine) met by RW, with the amount of additional MW required to meet irrigation demand (including GW top-up). These volumes are presented for a range of tank sizes and the percentage of payback, or 'MW Neutrality', is provided.

Table 19: Mains Water Neutral Gardening water balance by tank size for case study 2.

Tank volume (kL)	**Internal demand supplied by RW (kL)**	**Irrigation demand (kL)**	**GW irrigation supplementary MW required (kL)**	**MW neutral (%)**
2.5	28.1	19.29	3.8	122
3.5	29.5	19.29	3.8	128
5	31.1	19.29	3.8	135
7.5	33.5	19.29	3.8	145
10	35.4	19.29	3.8	153

It can be seen that a 2.5kL tank will provide adequate RW supply to the toilet and washing machine so as to offset the volume of MW required for irrigation (including GW top-up), with diminishing returns for increasing storage.

5.6 MONITORING

5.6.1 MONITORING SCOPE & PURPOSE

Monitoring of CS2 was undertaken between February and October 2012 for the purpose of assessing the contribution of GW to meeting garden water demand, and whether the volume of RW used inside for toilet flushing and washing machine use offset outside MW use, thus making the garden MW neutral. As monitoring was only undertaken over a nine-month period, the performance results were annualised based on comparable months with similar seasonal conditions.

Information on the equipment and methods used is provided in the following section, and details on assumptions and qualifiers are provided alongside the relevant data summaries in Section 5.7 (Results and Analysis).

5.6.2 MONITORING MATERIALS & METHOD

The property's water meter was fitted with a single channel, battery operated data logger. An additional three 20mm Elster V100 cold water meters with data loggers of the same type were installed to monitor sub meter irrigation (I) and garden tap (GT) volumes, as well as capture RW yield (RW). The metering arrangement also allowed for the determination of the combined volume of RW supplied to the toilet (T) and washing machine (WM), via:

$$RW_{T+WM} = RW - RW_{GT}$$

The loggers were set to record on a daily time-step basis.

GW volumes were estimated on a proportion of indoor volumes as described in Section 5.7.1.

5.7 RESULTS & ANALYSIS

5.7.1 HOUSEHOLD WATER USE BY SOURCE

Figure 20 compares CS2 household water use by source for the study period with the Perth average, as well as the local suburb average (White Gum Valley). The Perth average has been calculated using the same household occupancy rate as the case study site for practical comparison, whereas the local suburb data average is indicative of typical household use in the area. Total MW use for the CS2 was 84kL/annum compared to 301kL/annum for the Perth average and 247kL/annum for the local suburb average. The total indoor water use at CS2, of which RW comprised 26% (22kL), was 54% and 41%

less than the Perth and local suburb averages respectively. External water use at the CS2 was less than the Perth average and local suburb average (63kL/annum compared with 116kL/annum and 104kL/annum respectively) and MW use was 82% and 80% less respectively. It was complemented by the use of 2kL/annum and 40kL/annum of RW and GW respectively. In total, CS2 made use of 24kL/annum of RW using a 2.5kL tank with an effective roof catchment of 70m^2.

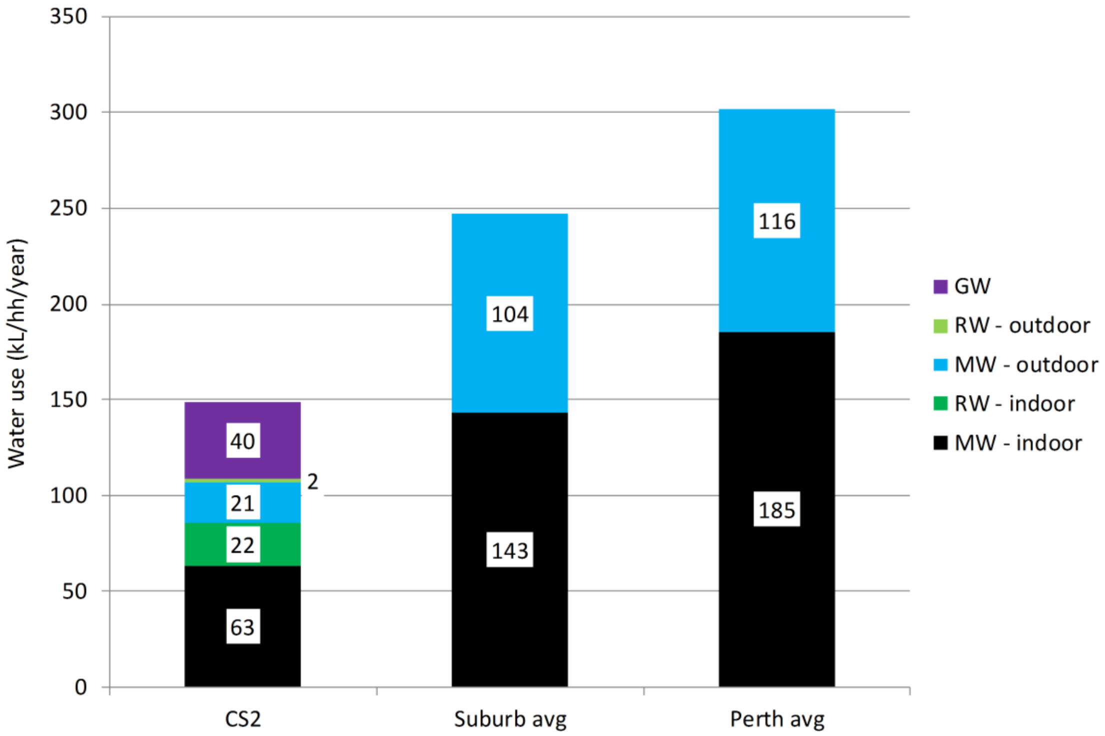


Figure 20: Water use by source at case study 2.

ASSUMPTIONS & QUALIFIERS

Annual indoor MW indoor use was established by extrapolating average daily data obtained from the property meter minus the MW used for irrigation and garden tap over a 184-day period (between 1 March and 31 August) and then annualised.

Annual indoor and outdoor RW volumes were established by analysing daily RW use between February and October 2012. Daily indoor and outdoor RW use volumes were determined by subtracting toilet, washing machine, and backyard tap water use from the by rain meter reading and surplus RW from the previous day. If there was insufficient RW to service all three items, RW was allocated in the following order: toilet, washing machine, and backyard tap. These figures also took into account inefficiency in the operation of the mains water backup valve (MWBV), i.e. each time the RW was drawn, some MW was also used. The MWBV inefficiency (i.e. percentage of MW used when

RW was available) was calculated over time periods where RW was available. Based on experience from CS1, a 10% inefficiency factor was applied to account for MW mixing. The results were annualised by assuming that water use patterns in November were similar to those in April, and December and January were similar to February.

Annual outdoor MW use was established by extrapolating average daily data obtained from the irrigation meter and MW use from the garden tap over a 241-day period between 11 February and 8 October 2012. Again, the results were annualised by assuming that water use patterns in November were similar to those in April, and December and January were similar to February.

Annual GW volumes were based on an estimated proportion of 62.5% of metered internal water (IW) used, given bathroom and laundry GW typically makes up this portion of internal water consumption (Water Corporation, 2010). Internal water use was calculated via:

$$IW = PM + RW_{T+WM} - (I + GT_{MW})$$

where:

PM = Property Meter
T = Toilet
WM = Washing Machine
I = Garden Tap

No GW volumes were assumed from June to August as the system was switched off during the winter months.

The suburb average water use figures were sourced via the Water Corporation (D. Elletson, personal communication, 21 Jan, 2016). The 58% (indoor use) to 42% (outdoor use) split is based on the 2008/09 PRWUS (Water Corporation, 2010).

The Perth average water use figures were extrapolated from data presented in the 2008/09 PRWUS (Water Corporation, 2010), with the indoor water consumption scaled to the number of occupants, but fixing the quantity used for irrigation as this component is unlikely to change regardless of the number of occupants. The PRWUS (2010) states the average annual household water use is 277kL based on 2.6 residents, with 58% used for indoor purposes. This equates to 61.8kL per person per annum for indoor water use and 116kL/annum for outdoor water use. This translates to an indoor water use of 185kL/annum for a three-person household.

5.7.2 GREYWATER VOLUMES – ACTUAL VS MODELLING

Figure 21 expresses the average daily GW volumes of 148L per day recorded at CS2 as an irrigation application rate of 3.7mm per day over the 40m^2 dispersal area, as well as the modelled projected GW application rate of 4.6mm based on an estimated GW generation rate of 183L per day. Running alongside is the monthly water demand of the plants in the GW Hz, assuming a plant crop factor of 0.6 and an irrigation application IEf of 95%. This results in a deficit of 11.3kL between the months of November to March, compared to the expected deficit of 5.9kL estimated by the modelling, with the reduced GW volumes resulting from low-water-use behaviour displayed by the occupants.

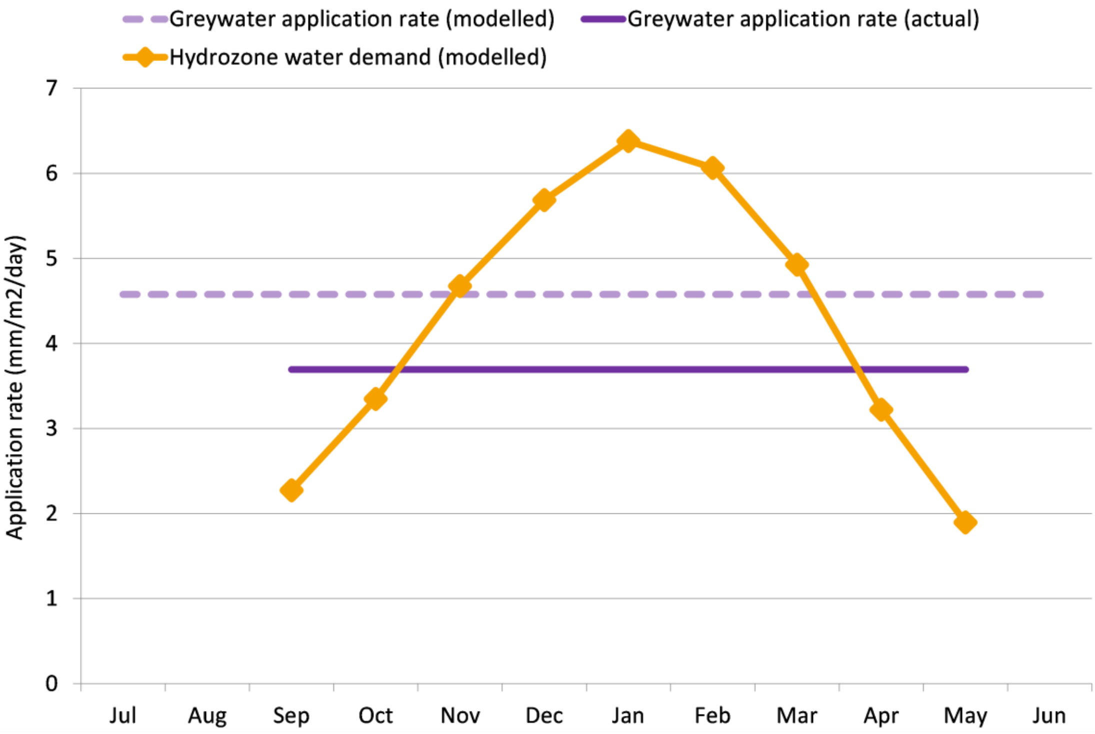


Figure 21: Modelled versus actual greywater volumes generated at the case study 2 expressed as an irrigation application rate (location of Perth, Western Australia).

ASSUMPTIONS & QUALIFIERS

GW volumes were based on an estimated proportion of 62.5% of metered internal water (IW) used given bathroom and laundry GW typically makes up this portion of internal water consumption (Water Corporation, 2010), as described in Section 5.7.1.

5.7.3 RAINWATER VOLUMES – ACTUAL VS MODELLING

Table 20 presents the garden water use and inside non-potable water use volumes by source for each month, as well as proportion of RW and MW consumed. It can be seen that MW use was approximately 17kL for irrigation and 4.4kL for garden tap, totalling 21.4kL, compared to the 22.4kL of RW used for indoor purposes (toilet and washing machine). This shows that MWNG was achieved, with 105% of MW used for garden purposes offset.

Table 20: Garden and indoor non-potable water use volumes by source for case study 2.

<table>
<tr><th></th><th>Irrigation
(kL)</th><th colspan="2">Garden tap
(kL)</th><th colspan="2">Toilet & Washing machine
(kL)</th></tr>
<tr><td></td><td>MW</td><td>RW</td><td>MW</td><td>RW</td><td>MW</td></tr>
<tr><td>January</td><td>3.5</td><td>0.2</td><td>0.8</td><td>0.3</td><td>3.1</td></tr>
<tr><td>February</td><td>3.5</td><td>0.2</td><td>0.8</td><td>0.3</td><td>3.1</td></tr>
<tr><td>March</td><td>2.5</td><td>0.0</td><td>0.8</td><td>0.0</td><td>3.7</td></tr>
<tr><td>April</td><td>1.2</td><td>0.1</td><td>0.2</td><td>1.9</td><td>1.6</td></tr>
<tr><td>May</td><td>0.6</td><td>0.1</td><td>0.1</td><td>2.7</td><td>1.0</td></tr>
<tr><td>June</td><td>0.1</td><td>0.0</td><td>0.1</td><td>2.7</td><td>0.9</td></tr>
<tr><td>July</td><td>0.0</td><td>0.8</td><td>0.1</td><td>2.4</td><td>1.2</td></tr>
<tr><td>August</td><td>0.1</td><td>0.0</td><td>0.1</td><td>3.3</td><td>0.4</td></tr>
<tr><td>September</td><td>0.1</td><td>0.0</td><td>0.1</td><td>3.2</td><td>0.4</td></tr>
<tr><td>October</td><td>0.6</td><td>0.1</td><td>0.1</td><td>3.3</td><td>0.4</td></tr>
<tr><td>November</td><td>1.2</td><td>0.1</td><td>0.2</td><td>1.9</td><td>1.6</td></tr>
<tr><td>December</td><td>3.5</td><td>0.2</td><td>0.8</td><td>0.3</td><td>3.1</td></tr>
<tr><td>Total</td><td>17.0</td><td>1.8</td><td>4.4</td><td>22.4</td><td>20.3</td></tr>
<tr><td>% Supply</td><td>NA</td><td>29</td><td>71</td><td>52</td><td>48</td></tr>
<tr><td colspan="4"><i>From Section 5.5.3</i>
Modelled RW Consumption (kL/annum)</td><td colspan="2"><i>From table above</i>
Actual RW Consumption (kL/annum)</td></tr>
<tr><td colspan="4">28.1</td><td colspan="2">24.2</td></tr>
</table>

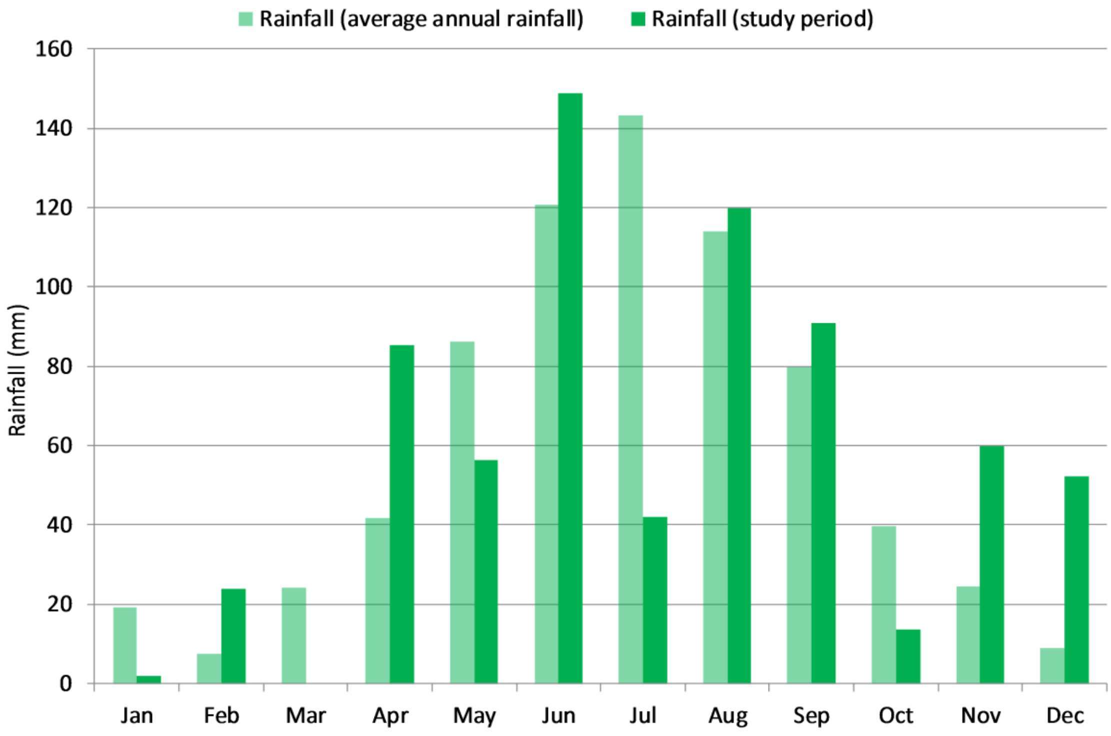


Figure 22: Comparison of rainfall during study period (2012) and recent average (1996–2010) for case study 2 (using data from Bureau of Meteorology Station 009215).

Figure 22 presents the local rainfall during the study period (695mm) with the recent average of 709mm (1996–2010) used for the modelling by month. Of note is that the average monthly rainfall during the study period was mostly higher than the recent average across rainy winter months and dry summer months. However, rainfall in July during the study period (42mm) was significantly lower than its recent average (143mm).

ASSUMPTIONS & QUALIFIERS

RW volumes and usage patterns were determined by establishing daily averages based on metered data collected between February and October 2012 and then extrapolated (including an allowance for MWBV inefficiency) as described in Section 5.7.1. The results were annualised by assuming that water use patterns in November were similar to those in April, and December and January were similar to February.

The rainfall data presented in Figure 22 was sourced from the Bureau of Meteorology station in Swanbourne.

5.7.4 IRRIGATION – ACTUAL VS MODELLING

Figure 23 presents the modelled irrigation demand of Hzs serviced by MW, compared against actual irrigation volumes applied. The graph indicates that actual irrigation falls short of its modelled expectations for most months, with 19.3kL/annum being modelled and 17kL/annum applied.

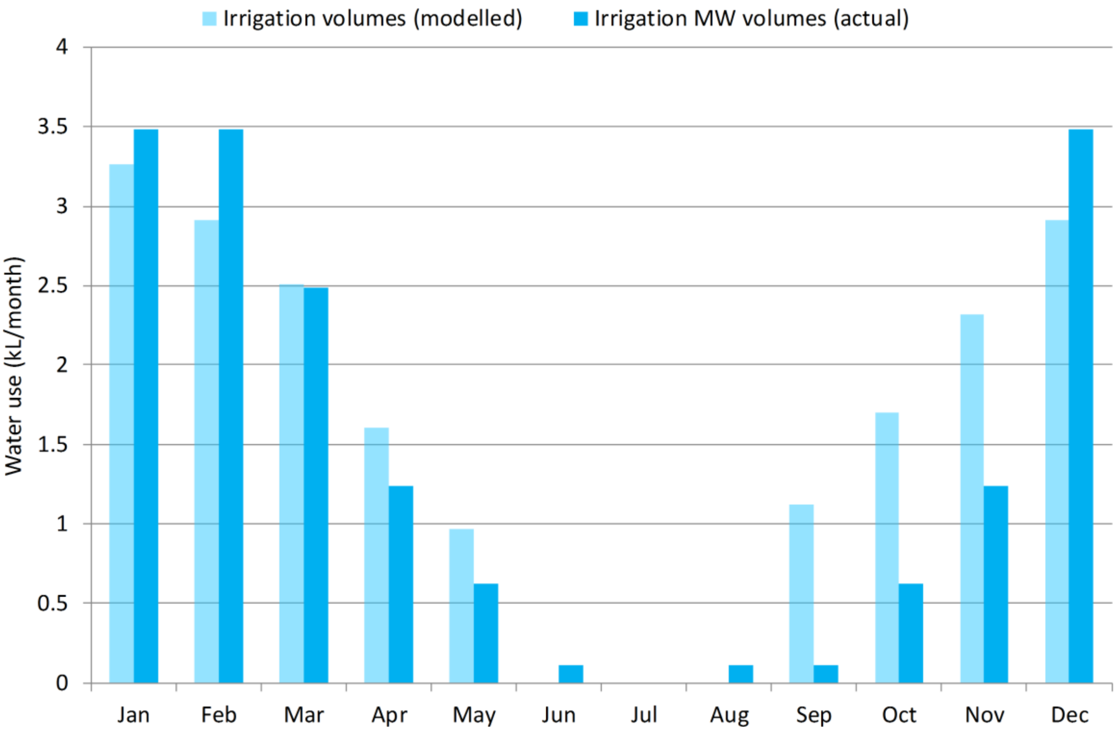


Figure 23: Comparison of modelled irrigation demand vs actual usage for CS2.

Reduced irrigation volumes in September and November of the study period can be attributed to good rainfall recorded for these months and hand watering via the garden tap being used for meeting garden water needs rather than running the irrigation system.

ASSUMPTIONS & QUALIFIERS

Irrigation volumes were established via metering over a 241-day period (11 February to 8 October 2012). The remaining months were estimated by assuming that water use patterns in November were similar to those in April, and December and January were similar to February, as described in Section 5.7.1.

5.8 REFLECTIONS & LESSONS LEARNED

5.8.1 WATER SYSTEM EQUIPMENT PERFORMANCE

GREYWATER SYSTEM

The GW system performed well during the monitoring period with no malfunctions. The automatic filter back flushing largely eliminated the need for manual filter cleaning during regular operation. Manual filter cleaning was undertaken when the system was switched back on after the winter months (June–August) when GW was not required for the garden. The relative ease of installation when compared to the tank system installed at CS1 was also a major advantage, only taking approximately four hours and causing minimal disturbance.

One disadvantage of the system is the loss of some GW capture during back flushing cycles, at which time air is blown through the polyethylene filter pads and the GW running through the system is used to remove dislodged solids and direct the material to sewer. The metering arrangement did not allow for the quantification of this lost volume, however observation by the author suggests it is likely to be around 5–10% of total GW volume.

RAINWATER SYSTEM

The RW system also performance well during the monitoring period with no malfunctions recorded. Given the simple arrangement of the system components using an above-ground take, installation was straightforward, including the retrofitting of the roof drainage and pumped RW supply to the nominated demands.

IRRIGATION SYSTEM

The irrigation system for CS2 was supplied solely by MW to eliminate the issue of pressure variation between RW and MW supplies as experienced with CS1. Careful management of the irrigation scheduling (by the author) combined with the inclusion of an evapotranspiration-based controller meant that irrigation volumes that were metered were in line with the modelled demands.

5.8.2 MONITORING METHODOLOGY & RELIABILITY OF DATA

Due to budget constraints, the metering deployed at CS2 was restricted to essential parameters to assess whether MWNG status could be achieved (i.e. MW and RW supply, plus garden irrigation and garden tap demands, with RW supply to toilet and washing machine established via subtraction). Whilst this arrangement proved adequate to establish that MWNG was in fact achieved, intermittent issues with the single channel, battery opperated data loggers resulted in the data being incomplete across the year, and the need for data extrapolation to present results across a 12-month period.

Technical challenges with the metering of greywater from GDDs without a settling tank (i.e. meter fouling) meant that GW volumes were based on best estimations only as outlined in Section 5.7.2, limiting the value of this data to verify assumptions used in the modelling. This experience informed the development of a pre-meter filtration method for GW to enable metering which was subsequently deployed at CS3 in order to get better quality data.

5.8.3 ALTERNATIVE WATER SYSTEM COSTS & PAYBACK PERIODS

GREYWATER SYSTEM

Table 21 presents the supply, installation and operational costs for the GW system at CS2. The cost build-up is shown by item, along with the estimated life span / replacement intervals and annualised costs. The total cost over life of the system is estimated to be $5,227 assuming an operational life of 20 years (Memon *et al*., 2005). This equates to $261 per year when annualised over this period, or $6.53/kL based on the 40kL of GW supplied by the system. Using a reference figure of $1.59 per kL[1] for MW suggests a payback period of 82 years, which is well beyond the expected life span of the system. The system operating costs including electricity, plus annualised pump, blower, controller and filter replacement is approximately $154 per annum.

The GW system costs are for the supply and install of the GDD only, plus all associated plumbing, but does not include the dripline irrigation component as this cost would be covered in a typical business as usual (BAU) irrigation installation (which is around $10/m^2 for dripline).

The cost of the GW system is within the typical range for GDDs of this type and functionality (ATA, 2009).

Table 21: Greywater system costs for case study 2.

Greywater system items	**Capital cost ($)**	**Estimated life/ replacement intervals (Yrs)**	**Annualised cost ($)**	**Life of system costs ($)**	**NPV ($)** Discount rate: 7%
GW system - initial supply and install	1850	20	93	1850	1850
Hired labour for plumbing modifications	300	20	15	300	300
GW pump replacement	350	7.5	47	933	688
Blower replacement	300	7.5	40	800	589
Controller replacement	250	7.5	33	667	491
Filter replacement	50	7.5	7	133	98
Labour	150	7.5	20	400	295
Maintenance (by user)	0	NA	0	0	0
Power per annum (0.69kWhr/kL) @ $0.26/kW[2]	7	20	7	144	76
GW system - cost over life	3257	20	261	5227	4387

[1] The unit cost of water is based on local supply charges for MW taking into account the tariff tiers relative to the total property water consumption (Water Corporation, 2016).

[2] Local supply flat tariff rate (Synergy, 2016).

RAINWATER SYSTEM

Table 22 presents the supply, installation and operational costs for the RW system at CS2. The cost build-up is shown by item, along with the estimated life span / replacement intervals and annualised costs. The total cost over the life of the system is estimated to be $5,315 assuming an operational life of 20 years (Gurung *et al.*, 2012). This equates to $262 per year when annualised over this period, or $10.98 per kL based on the 24kL of RW supplied by the system. Using the figure of $1.59 per kL for MW suggests a payback period of 138 years, which is well beyond the expected life span of the system. The system operating costs including electricity, plus annualised pump and MWBV replacement is approximately $116 per annum.

Table 22: Rainwater system costs for case study 2.

Rainwater system items	**Capital cost ($)**	**Estimated life/ replacement intervals (Yrs)**	**Annualised cost ($)**	**Life of system costs ($)**	**NPV ($)** Discount rate: 7%
RW Tank	1000	20	50	1000	1000
RW Pump & Mains Water Back Up Valve	1000	20	50	1000	1000
Hired labor for plumbing modifications	1000	20	50	1000	1000
RW pump replacement	500	10	50	1000	754
MWBV replacement	500	10	50	1000	754
Maintenance (by user)	0	NA	0	0	0
Power per annum (2.5 kWhr/kL) @ $0.26/kW	16	20	16	315	167
RW system - cost over life	4016	20	266	5315	4675

The RW system costs are for the tank, pump, MWBV and associated roof drainage and RW plumbing supply modifications; they do not include original roof guttering costs as these are also required in a BAU roof drainage scenario. The initial install cost and cost over life of the system ($3,000 and $5,339 respectively) are in line with costs published in the literature for simple installations using standard materials and equipment (Coombes *et al.*, 2003; Gurung *et al.*, 2012).

The limitations of using a payback model based on MW cost per kilolitre savings is discussed in Chapter 7 (Discussion) and Chapter 8 (Conclusion).

INTENTIONALLY BLANK PAGE

CHAPTER 6: CASE STUDY 3

6.1 CHAPTER INTRODUCTION

This chapter covers the last of three case study gardens (CS3) that were designed and built by the author as part of this study based on the Sustainable Urban Gardening (SUG) and Mains Water Neutral Gardening (MWNG) concepts. The chapter begins with an overview of CS3 (Section 6.2) followed by a description of the landscape design and SUG attributes (Section 6.3).

Section 6.4 describes the water system infrastructure installed, including greywater (GW), groundwater (GndW) bore, rainwater (RW) and irrigation systems. Section 6.5 presents the water balance modelling underpinning the MWNG landscape design, including estimated GW volumes, garden water requirement, GndW extraction and recharge volumes, RW yield, as well as the projected MWNG outcome.

Section 6.6 describes the water usage monitoring undertaken post garden establishment, including equipment and techniques used. The results and analysis of the findings are described in Section 6.7 and details on lessons learned from this case study are provided in Section 6.8. Further discussion is provided in Chapter 7 (Discussion), along with the other two case studies for comparison.

6.2 CASE STUDY OVERVIEW

CS3 is a three bedroom, two bathroom, detached dwelling located on a 700m^2 block in the Perth suburb of Hilton in Western Australia where the local climate type is classified as Mediterranean (Bureau of Meteorology, 2015) and the soil type is coarse sand, typical of the Karrakatta soil association of the Spearwood dune system of that area (McArthur, 2004).

The house was built in 2013 and included dual plumbing for RW supply to all indoor uses and dual plumbing for GW collection from all GW sources (excluding kitchen sink and dishwasher). Water-efficient plumbing fixtures were installed throughout. A data dashboard with real-time user feedback on daily water use by source (as well as a range of other household operational parameters, such as electricity and gas usage) was also installed with the aim of informing responsible consumption patterns.

The property was serviced by RW for all internal demands (i.e. potable and non-potable) with mains water (MW) backup, with the dual plumbing to non-potable demands intended to provide flexibility (e.g. if future occupants want to use RW for toilets and washing machine only). Garden demands were serviced by both GW and GndW via a bore. More information on the equipment installed at CS3 is provided in Section 6.4 (Water System Infrastructure).

As a three-bedroom house, occupancy was four persons during the study period (the author and his family). The occupants included two adults in the 31–40 year age group (one male and one female) and two children under five years (one male and one female).

6.3 LANDSCAPE DESIGN

6.3.1 DESIGN INTENT & PROJECT INSIGHTS

The brief for the landscape design was to create family spaces for outdoor living, as well play spaces for young children. Strategic placement of trees and vines was to be an important consideration to enhance the thermal performance of the solar passive–designed home. Food production was to be a major theme, with adequate space set aside for growing fruits and vegetables, with composting systems and nursery included to support these activities. The garden was to be managed organically so considerations were to be made for natural pest and disease management plus the consideration of urban biodiversity more broadly.

6.3.2 SUSTAINABLE URBAN GARDENING FRAMEWORK & DESIGN RESPONSE

Table 23 provides a summary of the key landscape design elements and supporting gardening activities at CS3 in response to the SUG framework developed by the author. The landscape design prepared for the property is presented as Figure 24. Where relevant, an alphanumeric reference has been listed alongside the landscape design elements in the table correlating to their location on the landscape plan. Photographs are provided in Figure 25 for further context and detail, using the same reference key.

Table 23: Summary of the sustainable landscape design elements and supporting gardening activities for case study 3.

SUSTAINABILITY GOAL 1: ENERGY EFFICIENCY	
Desired Outcomes	**Design Elements & Gardening Activities**
Reduced fossil fuel use from embedded energy in materials and in the operations of the house and garden.	Strategic positioning of trees and vines for aiding thermal performance of the house (1A). Repurposed and reclaimed timber used throughout and locally sourced stone used (1B). The use of concrete kept to a minimum. ‘Low carbon concrete’ used (1C).
SUSTAINABILITY GOAL 2: ORGANIC WASTE RECYCLING & SOIL MANAGEMENT	
Desired Outcomes	**Design Elements & Gardening Activities**
Local soil carbon regeneration and nutrient recycling.	Composting bins to recycle house and garden organic waste (2A). Soil conditioning and mulching to increase soil carbon and naturally improve soils over time (2B).
SUSTAINABILITY GOAL 3: BIODIVERSITY & HABITAT RESTORATION	
Desired Outcomes	**Design Elements & Gardening Activities**
Enabling indigenous plant, insect and animal life to thrive.	Considered plantings (native and exotic) to provide food source for insects and birds (3A). Rubble rock walls and logs providing habitat for insects and lizards (3B). Deep mulching and leaf litter accumulation to encourage invertebrates and bird foraging (3C).
SUSTAINABILITY GOAL 4: ORGANIC PEST & DISEASE MANAGEMENT	
Desired Outcomes	**Design Elements & Gardening Activities**
Achieving natural ecosystem functioning that controls pests and weeds without toxic chemical use.	Companion planting to encourage predatory insects and pest distraction (4A). Design allows for crop rotation of vegetables (4B). Design allows for effective deployment of cultural practices for organic pest and weed control (4C).

SUSTAINABILITY GOAL 5: FOOD PRODUCTION	
Desired Outcomes	**Design Elements & Gardening Activities**
Local food production contributing to household food supply.	Space allocated for intensive vegetable growing (5A). Fruit trees and vines in garden beds and on trellis systems (5B). Diverse range of edible species throughout the landscape (5C). Edible aquatic plants included in water features (5D). Keeping poultry for eggs (5E).
SUSTAINABILITY GOAL 6: WATER CONSERVATION	
Desired Outcomes	**Design Elements & Gardening Activities**
Reducing water-based ecological footprint.	Effective hydrozing for effective irrigation management (refer Figure 26). Efficient irrigation system (6A). GW applied to appropriate hydrozone (Hz) (6B). GndW for irrigation with extraction based on local water balance to determine sustainable yield (6C). RW harvesting – indoor use only (6D). Water efficient gardening practices deployed including soil building, mulching and plant selection/care (refer Attachment 1).
SUSTAINABILITY GOAL 7: HEALTH AND WELLBEING OF HOUSEHOLDERS	
Desired Outcomes	**Design Elements & Gardening Activities**
Achieving a liveable housing habitat including daily contact with nature.	Landscaping enhances thermal performance for house, increasing occupant comfort (7A). High quality outdoor living areas providing regular contact with garden (7B). Engaging outdoor play features for children (7C). Fresh food available from garden (7D).

Figure 24: Landscape plan for case study site 3.

Figure 25: Photographs of case study site 3 (photo credits: J. Barbitta; B. Hutchens; Rob Frith and J. Byrne).

1A: Strategic positioning of trees, vines and shading devices for aiding thermal performance of the house.

1B: Use of repurposed and reclaimed timber, and locally sourced stone.

1C: The use of concrete kept to a minimum. Low carbon concrete used.

2A: Composting bins to recycle house and garden organic waste.

2B: Soil conditioning and mulching to increase soil carbon and naturally improve soils over time.

3A: Considered plantings to provide food source for insects and birds.


3B: Rubble rock walls and logs providing habitat for insects and lizards.


3C: Deep mulching and leaf litter accumulation to encourage invertebrates and bird foraging.


4B: Design allows for crop rotation of vegetables.


4A: Companion planting to encourage predatory insects and pest distraction.


4C: Design allows for effective deployment of cultural practices for organic pest and weed control.

5A: Space allocated for intensive vegetable growing.

5B: Fruit trees and vines in garden beds and on trellis systems.

5C: Edible aquatic plants included in water features.

5D: Diverse range of edible species throughout the landscape.

5E: Poultry for supply of eggs.

6A(i): Irrigation system – solenoid valves.

6A(ii): Irrigation system – controller.

6A(iii): Irrigation system – rain shutoff switch.

6A(iv): Irrigation system – dripline.

6A(v): Irrigation system – pot sprays.

6B(i): Greywater system – access covers to sumps and submersible pump.

6B(ii): Greywater system – Dripline.

6C: Groundwater bore.

6D(i): Rainwater system – 20kL tank.

6D(ii): Rainwater system – rain head with leaf screens.

6D(iii): Rainwater system – pump and mains water backup valve.

7A: Landscaping enhances thermal performance of the house, increasing occupant comfort.

7B: High quality outdoor living areas providing regular contact with the garden.

7D: Fresh food available from the garden.

7C: Engaging outdoor play features for children.

6.4 WATER SYSTEM INFRASTRUCTURE

6.4.1 GREYWATER REUSE SYSTEM

The greywater diversion device (GDD) at CS3 was a proprietary system known as the ‘GreyFlow PS-Two Stage’ by Advanced Wastewater Systems (WA Department of Health approval number WMKT 21323), which was installed as per the WA Department of Health *Code of Practice for the Reuse of GW in Western Australia* (Department of Health, 2010).

The system was based on the same principles of operation as the unit installed at CS2, with the difference being that the two-stage unit was designed for installation with ‘slab on ground’–type house construction. The GW interceptor traps and the pump sump were installed as part of early plumbing works during construction (stage one) and pump, filter pads, blower (for back flushing), controller and drip irrigation installed during landscaping irrigation works (stage two).

Photographs of the key features and general arrangement of the GW system installed at CS3 are shown in Figure 25, photo 6B(i)–6B(ii) (page 112).

6.4.2 RESIDENTIAL GROUNDWATER BORE

GndW was extracted at CS3 from the superficial aquifer via a bore drilled to a depth of 25m fitted with a variable speed submersible pump. The bore serviced two properties (the case study site and neighbouring block), supplying water for garden irrigation, GW top-up and garden taps.

Photographs of the key features and general arrangement of the GndW bore installed at the CS3 are shown in Figure 25, photo 6C (page 113).

6.4.3 RAINWATER HARVESTING SYSTEM

The RW harvesting system at CS3 was installed in accordance with *AS/NZS 3500 Plumbing and Drainage – Water Services* (Standards Australia, 2008), and the *RW Tank Design and Installation Handbook* (National Water Commission, 2008a).

Rain was harvested off 200m^2 of roof catchment (entire house roof area) via a ‘wet feed’ or ‘charged’ plumbing arrangement where the RW drainage pipework remains filled with water as it moves from the entry point at the rain head (with leaf trap) beneath the gutter outlet to the exit point at the tank inlet through gravity. A drain valve was installed at the end of the pipe run prior to entering the tank for line drainage and diversion of dirty roof water (e.g. first rains of the season).

RW was stored in an 18,000L above-ground corrugated steel RW tank with the overflow diverted to a soakwell. A pressure switch activated pump was connected to the tank, and a 90L pressure chamber vessel fitted to reduce pump start-up by meeting small demand events. Pressurised RW was supplied to all internal uses via a MW backup valve and water was treated with two-stage filtration and UV disinfection.

Photographs of the key features and general arrangement of the RW harvesting system as installed at CS3 are shown in Figure 25, photos 6D(i)–6D(iii) (page 113).

6.4.4 LANDSCAPE HYDROZONES & IRRIGATION SYSTEM

The landscape design at the CS3 was based on six Hzs as identified in Figure 26, with size and location of the various Hzs being determined by the designer’s response to available water, and prioritisation of gardening activities in line with the SUG framework.

The Mixed Perennials Hz (Hz1) received water from the GW system, which discharged as generated once the pump level switch was triggered. Plant selection included a range of species suited to untreated GW (Department of Health, 2010). The other Hzs included the Vegetables Hz (Hz2), Fruit Trees Hz (Hz3), Lawn Hz (Hz4), Pots Hz (Hz5) and Native Hz (Hz6). These received water via the GndW bore supply, with the timing of watering to Hz2–Hz6 being automated by a programmable multi-station irrigation controller fitted with a rain shut-off switch to help prevent unnecessary watering.

GW top-up from the bore is provided by two means. Firstly, a solenoid valve-operated line supplies water to the GW system via an overflow relief gully on the house GW drainage line (Josh Byrne and Associates, 2013). Opening the valve delivered water to the system replicating GW flows, in the same way as described for the previous two case study sites, which was ideal for periods when the house was unoccupied and irrigation is required across the entire Hz. The second means of top-up was via dual irrigation, where additional irrigation lines were used to deliver water to specific plants (or areas) within the Hz (Byrne *et al*., 2008). Here two separate solenoid-controlled lines were used, one for fruit trees and the other for herbs.

The design and installation of the irrigation system was undertaken in accordance with relevant irrigating industry standards (Cape, 2006; IA, 2012).

Photographs of the key features and general arrangement of the irrigation system installed at CS3 are shown in Figure 25.

Figure 26: Hydrozone plan for case study 3.

6.4.5 WATER SYSTEM INTEGRATION

Figure 27 shows the integration of the GW, GndW, RW and MW from source to sink. RW with MW backup services all internal demands, including kitchen sink and dishwasher, bathroom basins and showers/bath, laundry trough, toilets and washing machine. GW supplies Hz1 and GndW supplies Hzs 2–6, plus any top-up requirements to Hz1.

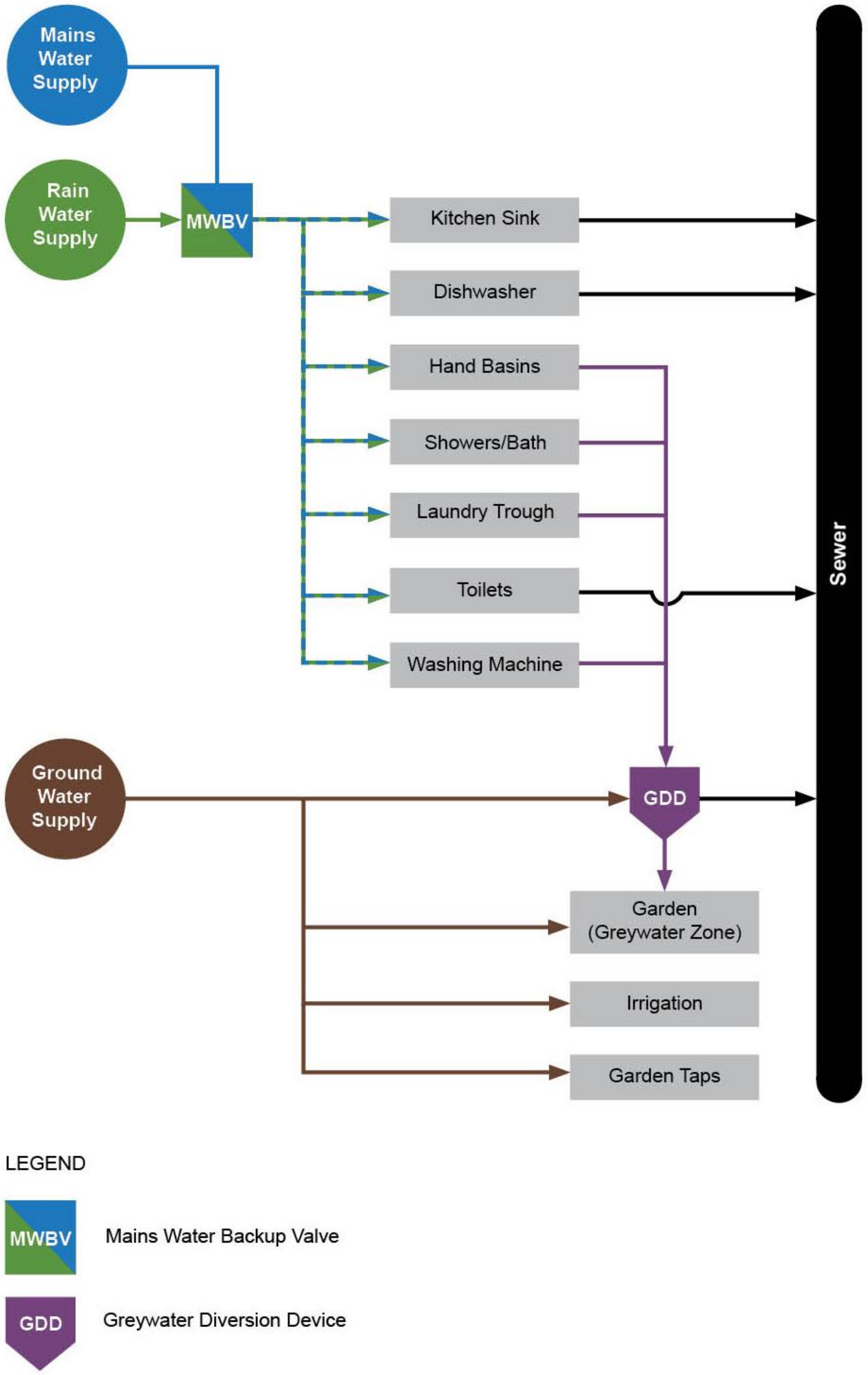


Figure 27: Water system design schematic illustrating the integration of the various water sources at the case study 3, including water flows from source to sink.

6.5 WATER BALANCE MODELLING

The following section outlines the water balance modelling for CS3 undertaken as part of the landscape design phase using a tailored spreadsheet tool developed by Hunt *et al.* (2011b). The modelling included estimation of GW volumes, estimated GndW recharge versus irrigation demand based on the MWNG objective, and estimated RW yield.

6.5.1 GREYWATER VOLUMES

Table 24 presents the estimated daily GW generation volumes used in Department of Health (2010) design guidelines, as well the projected GW volumes assuming a 30% reduction in water use based on the PRWUS (2010). The 30% reduction figure is comprised of 15% savings through the use of water-efficient fixtures above BCA requirements, and 15% savings through water-efficient behaviours (aided by real-time data display).

Table 24: Regulatory greywater design volumes compared to estimated volumes for case study 3.

GW source	**Design volumes*** (L/person/day)	**Water efficient volumes** (L/person/day)	**Water efficient volumes** **(**L/house/day = 4 people)
Bathroom	60	56.6	226.4
Laundry	40	17.2	68.8
Total	100	73.8	295.2

*Source: Department of Health (2010)

Figure 28 shows the estimated daily household generation of GW (295.2L per day) as providing an irrigation application rate of 7.4mm per day over the 40m^2 area. Running alongside is the Hz water demand, assuming a plant crop factor of 0.6 for mixed perennial species including hardy fruit trees and vines and an assortment of perennial understory shrubs, grasses and groundcovers. The Hz water demand also considers an irrigation application inefficiency (IEf) of 95%. It can be seen that GW volumes will be sufficient to meet irrigation demand year-round (during full occupancy).

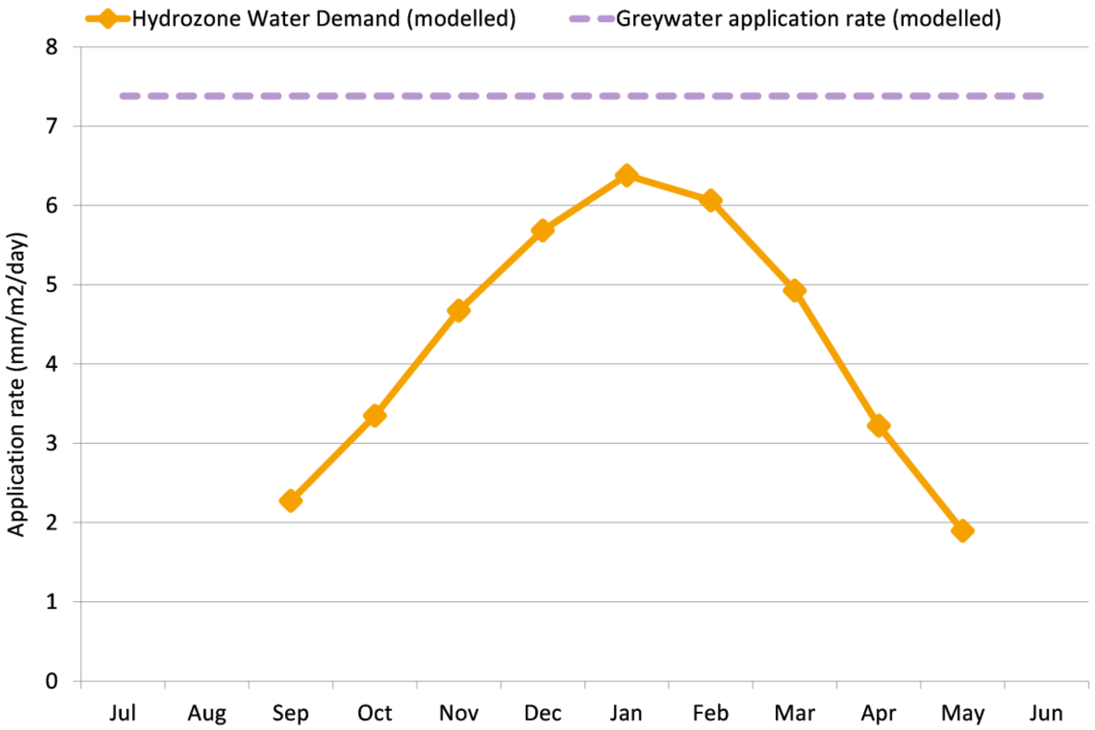


Figure 28: Estimated greywater application rates compared with estimated hydrozone water demand for case study 3 (location of Perth, Western Australia).

6.5.2 GROUNDWATER RECHARGE & EXTRACTION

Annual estimated site GndW recharge volumes were established as the basis for setting the amount of GndW available for irrigation via:

GWI = AARF x APS x GDWIF + (AARF x RA – RWY)*

*(or TO if known)

where:

AARF = Average Annual Rainfall (mm)

APS = Area of Permeable Surfaces (m^2)

GDWIF = GndW Infiltration Factor (%)

RA = Roof Area m^2

RWY = RW Yield (L)

RWY = Rainwater Yield

TO = Tank Overflow (L)

Modelling input values are presented below in Table 25.

Table 25: Rainwater modelling input values for case study 3.

Description	Abbreviation	Input value
Average Annual Rainfall (mm)	AARF	706[1]
Area of Permeable Surfaces (m^2)	APS	480
GndW Infiltration Factor	GDWIF	0.5[2]
Tank Overflow (L)	TO	39,000
GndW Infiltration (L)	GWI	-

[1] Average rainfall from Bureau of Meteorology weather station (Swanbourne) 1996–2010.

[2] Department of Water (2009)

Based on these values, approximately 208kL is available for irrigation.

6.5.3 IRRIGATION DEMAND

Irrigation volumes for the five Hzs serviced by GndW (Hz2–Hz6) were calculated for the purposes of estimating landscape water demand. Table 26 outlines the key information used in the modelling for each Hz.

Table 26: Hydrozone irrigation demand modelling inputs for case study 3.

Parameter	**Hz1** Mixed Perennials (GW)	**Hz2** Vegetables	**Hz3** Fruit Trees	**Hz4** Lawn	**Hz5** Pots	**Hz6** Natives
Area (m^2)	40	20	14.5	20	5	20
Crop factor	0.6	0.8	0.7	0.5	0.8	0.3
Root depth (m)	0.50	0.30	0.50	0.30	0.30	0.6
Canopy cover (%)	100	100	100	100	100	100
Irrigated by:	GW	GndW	GndW	GndW	GndW	GndW
Then by:	GndW	–	–	–	–	–

Table 27 presents estimated monthly irrigation demand for each Hz (kL) based on local evapotranspiration rates.

Table 27: Estimated irrigation demand by hydrozone (kL) for case study 3.

Month	**Evapo-trans. Rate* (mm/day)**	**Hz1** Mixed Perennials (GW)	**Hz2** Vegetables	**Hz3** Fruit Trees	**Hz4** Lawn	**Hz5** Pots	**Hz6** Natives	**Total (kL/month)**
January	10.1	7.91	5.27	3.35	3.91	1.46	1.98	23.88
February	9.6	7.03	4.69	2.97	3.48	1.30	1.95	21.42
March	7.8	6.11	4.07	2.58	3.02	1.13	1.53	18.44
April	5.1	3.87	2.58	1.63	1.91	0.71	1.00	11.70
May	3	2.35	1.57	0.99	1.16	0.43	0.59	7.09
June	2.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
July	2.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
August	2.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
September	3.6	2.73	1.82	1.15	1.35	0.50	0.70	8.25
October	5.3	4.15	2.77	1.76	2.05	0.77	1.04	12.54
November	7.4	5.61	3.74	2.37	2.78	1.04	1.45	16.99
December	9	7.05	4.70	2.98	3.49	1.30	1.76	21.28
Total kL/year	–	46.80	31.20	19.79	23.16	8.65	11.99	141.59

* Bureau of Meteorology Station 009215.

6.5.4 RAINWATER VOLUMES

RW harvesting modelling was performed using average daily rainfall data taken from the nearest Bureau of Meteorology weather station to ascertain likely RW yields (given the available roof catchment area and practical tank sizing considerations).

Although no RW is used for gardening purposes at CS3, the water modelling information is presented here for consistency with the other case studies and for later discussion. The modelling inputs are presented in Table 28. Given all internal demands are to be met by RW (with MW back-up), a 100L per person per day value has been used based on an estimated 30% efficiency gain (15% through hardware and 15% through behaviour) on the 2008/09 PRWUS (Water Corporation, 2010).

Table 28: Rainwater harvesting modelling outputs for case study 3, using daily time-step, supply-demand side modelling (Hunt *et al.*, 2011b).

Rainfall modelling inputs	
Catchment area (m^2)	220
Catchment efficiency (%)	90
Loss to adsorption (mm/event)	0.2
Occupancy rate	4
Demand (L/p/d)	100

Table 29 presents the modelling results, including estimated rainwater used under the different tank size scenarios noting there is limited increase in yield return relative to increasing the tank size, as well as reliability (percentage of time that water is available to meet demand) and satisfaction (proportion of demand met).

Table 29: Rainwater harvesting modelling outputs for case study 3.

Rainfall modelling outputs	**Tank volume (kL)**				
	10	15	18	25	100
Total water available (kL/year)	155.4	155.4	155.4	155.4	155.4
Annual overflow	47.7	42.2	39.0	31.9	1.0
Efficiency + adsorption loss (kL/year)	20.0	20.0	20.0	20.0	20.0
Average rainfall (mm/year)	706.2	706.2	706.2	706.2	706.2
Total demand (kL/year)	146.0	146.0	146.0	146.0	146.0
Reliability (% time)	58%	62%	65%	70%	92%
Satisfaction (volume)	60%	64%	66%	71%	92%
RW used (kL/year)	**87.7**	**93.3**	**96.4**	**103.5**	**134.4**

6.6 MONITORING

6.6.1 MONITORING SCOPE & PURPOSE

Monitoring of CS3 was undertaken between January 2015 and December 2015 for the purpose of assessing the contribution of GW to meeting garden water demand, plus the contribution of RW harvesting to MW reduction, and whether GndW extraction by bore for irrigation was replenished by local recharge, thus making the garden MW neutral. Information on the equipment and methods used is provided in the following section, and details on assumptions and qualifiers are provided alongside the relevant data summaries in Section 6.7 (Results and Analysis).

6.6.2 MONITORING MATERIALS & METHOD

Three separate 20mm Elster V100 cold water meters were fitted to determine MW, RW and GW volumes, noting a customised pre-filter was installed pre-meter on the GW line to prevent meter fouling. GndW volumes were recorded using a 40mm flow meter (MT-EX 40). Sub metering was also undertaken on the bore lines supplying garden taps and top-up via the GW system using 20mm Elster V100 cold water meters.

A Mercoid Series SBLT2 submersible level sensor was installed in the RW tank to record tank volumes.

Watt meters were installed on each of the power circuits supplying the GW, GndW bore and RW pumps for determining the energy intensity of the water sources.

All meters and sensors were connected to a multi-channel data logging unit for recoding data, with real-time user feedback available to householders via a web portal which was accessible from personal smart devices (phone and tablet).

6.7 RESULTS & ANALYSIS

6.7.1 HOUSEHOLD WATER USE BY SOURCE

Figure 29 compares the CS3 household water use by source for the study period with the Perth average and ‘Perth average with bore’, as well as the local suburb average (Hilton). The Perth averages have been calculated using the same household occupancy rate as the case study site for practical comparison, whereas the local suburb data average is indicative of typical household use in the area. Total MW use for the case study site was 29kL/annum compared to 313kL/annum for the Perth average with bore, 363kL/annum for the Perth average, and 214kL/annum for the local suburb average. The total indoor water use at the case study site was 57% and 14% less than the Perth averages and the local suburb average respectively. The case study site made use of 78kL/annum of RW for indoor water use, using a 18kL tank and an effective roof catchment of 200m^2, which equates to satisfying 73% of indoor water demand. External water use at the case study site was less than the Perth average with bore but higher than the Perth average and the local suburb average (131kL/annum compared with 506kL/annum, 116kL/annum and 90kL/annum respectively). The site does not use MW outdoors but instead makes primary use of GndW. It uses 86kL/annum of GndW (which is 80% less than the GndW use of the Perth average with bore) complemented by 47kL/annum of GW.

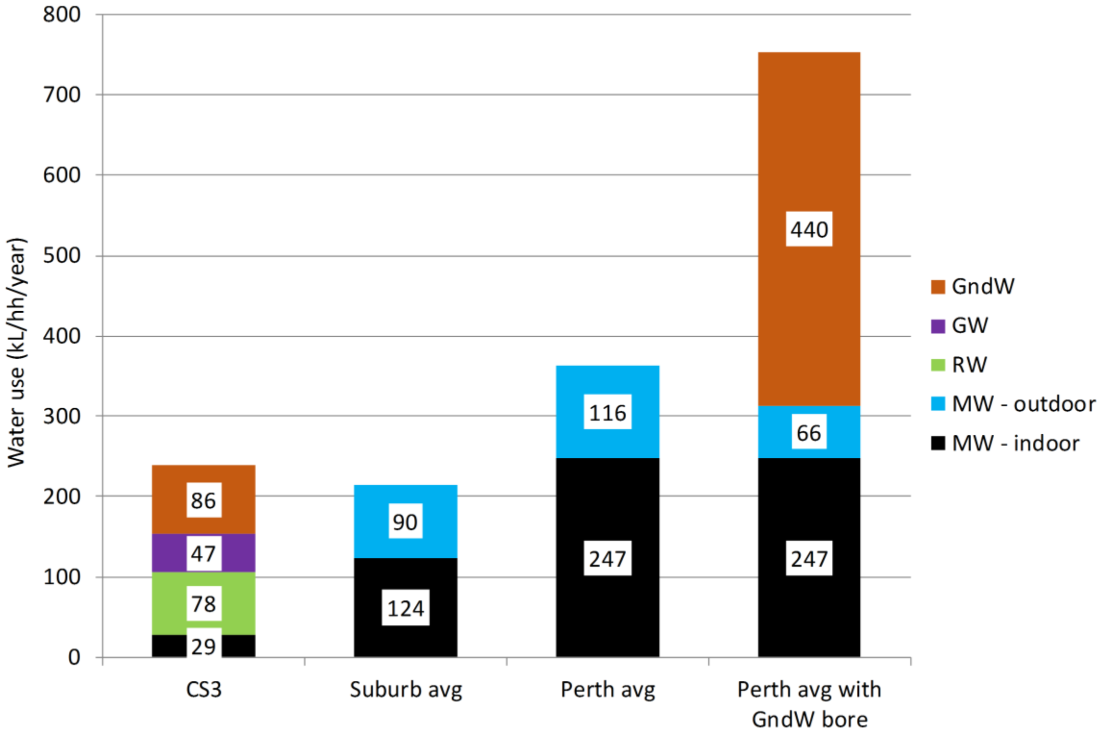


Figure 29: Water use by source for case study 3.

ASSUMPTIONS AND QUALIFIERS

Data for all water sources were obtained from water meters. The volumes for RW and MW were obtained directly from data logged across a 12-month period, from 1 January to 31 December 2015. The GndW bore supply services two properties (shared strata bore) and the meter captures the total volume for both properties. A 60% allocation is assigned to CS3 based on the balance of irrigated area.

An average daily GW volume of 173L per day was established from a sampling period of 84 days spanning 1 October to 24 December 2015. Regular cleaning of the meter pre-filter was undertaken during this period to minimise inaccuracies resulting from clogging. The daily average was extrapolated only over nine months to obtain the annual GW volume because the GW system is switched off over the winter months of June to August.

The suburb average water use figures were sourced via the Water Corporation (D. Elletson, personal communication, 21 Jan, 2016). The 58% (indoor use) to 42% (outdoor use) split is based on the 2008/09 PRWUS (Water Corporation, 2010).

The Perth average water use figures were extrapolated from data presented in the 2008/09 PRWUS (Water Corporation, 2010), with the indoor water consumption scaled to the number of occupants, but fixing the quantity used for irrigation as this component is unlikely to change regardless of the number of occupants. The PRWUS (Water

Corporation, 2010) states the average annual household water use is 277kL based on 2.6 residents, with 58% used for indoor purposes. This equates to 61.8kL per person per annum for indoor water use and 116kL/annum for outdoor water use. This translates to 247kL/annum for a four-person household.

According to the 2008/09 PWRUS, indoor MW use is the same for ‘Perth average with bore’ and Perth average. Outdoor water use is based on the Department of Water (2011) average Perth garden bore use figure of 440kL/annum. Additionally, households with a bore use an additional 66kL of MW for outdoor purposes.

6.7.2 GREYWATER VOLUMES – ACTUAL VS MODELLING

Figure 30 expresses the average daily GW volumes of 173L per day recorded at CS3 as an irrigation application rate of 4.3mm per day over the $40m^2$ dispersal area, as well as the modelled projected GW application rate of 7.4mm based on an estimated GW generation rate of 295.2L per day. Running alongside is the monthly water demand of the plants in the GW Hz, assuming a plant crop factor of 0.6 and an irrigation application IEf of 95%. This results in a deficit of 7.4kL between the months of November to March, compared to the expected deficit of zero predicted by the modelling. As per CS2, the reduced GW volumes result from lower water use in bathroom (shower and bath) and laundry (washing machine), and low-water-use behaviour displayed by the occupants.

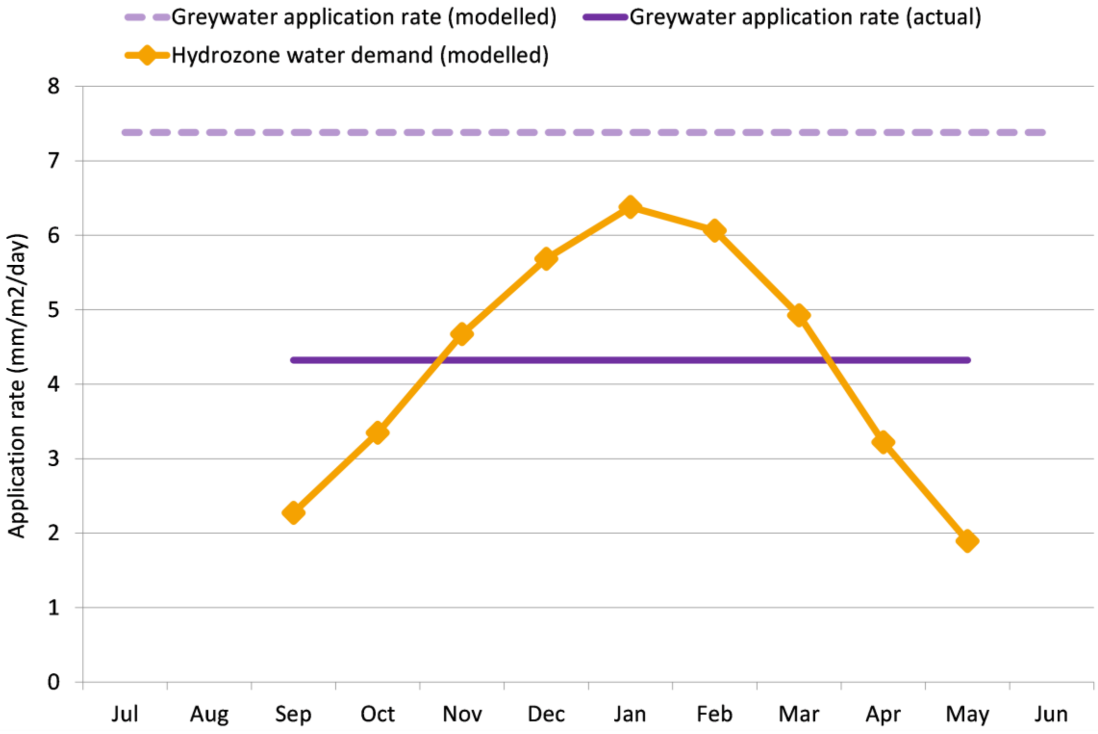


Figure 30: Modelled versus actual greywater volumes generated at the case study 3 expressed as an irrigation application rate (location of Perth, Western Australia).

ASSUMPTIONS & QUALIFIERS

As described above under the *Assumptions and Qualifiers* for Section 6.7.1, an average daily GW volume of 173L per day was established from a sampling period of 84 days spanning 1 October to 24 December 2015.

6.7.3 GROUNDWATER VOLUMES – ACTUAL VS MODELLING

Figure 31 shows the GndW extraction rates for irrigation and garden taps by month, as well as the average extraction rates over the year. Also shown is assumed GndW recharge rates averaged over the year based on actual rainfall during the monitoring period, compared with the estimated recharge rates based on the modelling. The annual rainfall for the year was 667mm compared to the recent average figure of 706mm used for the modelling so the estimated recharge rate was 6% less than expected. Total GndW extraction was 86kL compared to the modelled demand of 95kL and, as a result, it is estimated that more than double this amount was recharged into the aquifer (199kL/annum).

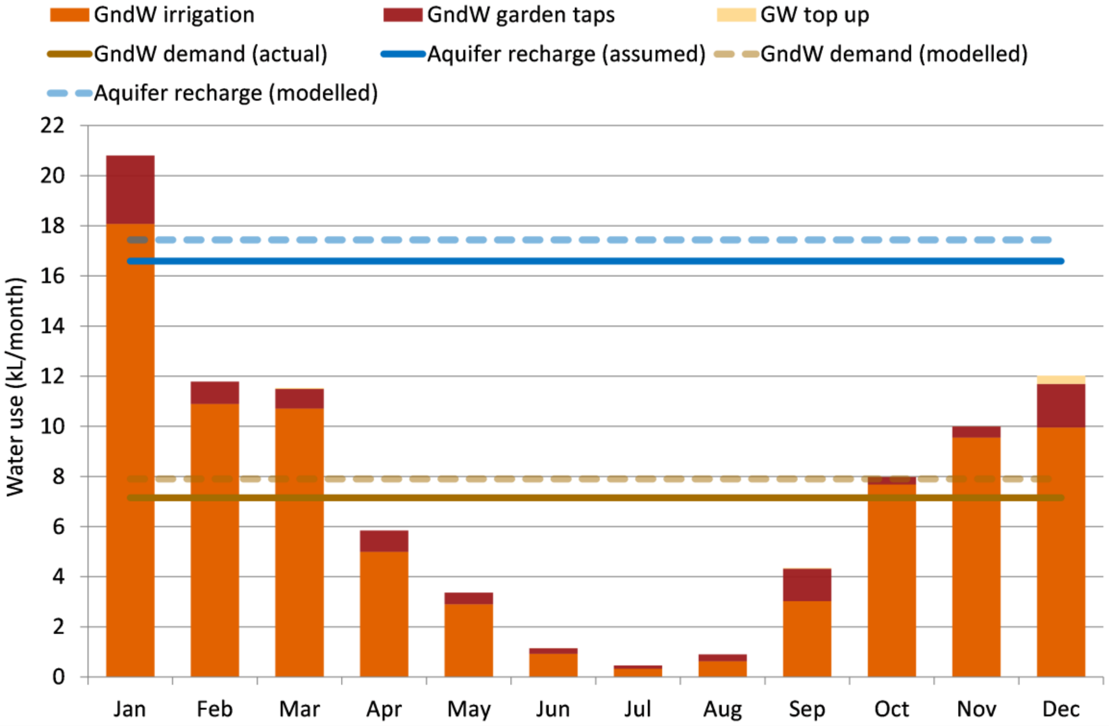


Figure 31: Groundwater extraction and assumed recharge volumes (shown as an average over the year) for case study 3.

ASSUMPTIONS & QUALIFIERS

As described above under the *Assumptions and Qualifiers* for Section 6.7.1, GndW volumes were logged across a 12-month period, from 1 January to 31 December 2015. The GndW bore supply services two properties (shared strata bore) and the meter captures the total volume for both properties. A 60% allocation is assigned to CS3 based on the balance of irrigated area as described in Section 6.7.1.

6.7.4 IRRIGATION – ACTUAL VS MODELLING

Figure 32 compares the modelled irrigation volumes with actual irrigation demands from the study period. Generally, actual irrigation volumes were in line with modelled values with the exception of January, where actual use exceeded modelled use by approximately 20%. The reason for this can be partially attributed to additional GndW being applied to the GW Hz to compensate for low GW volumes being generated, plus additional garden watering occurring over the hottest time of the year.

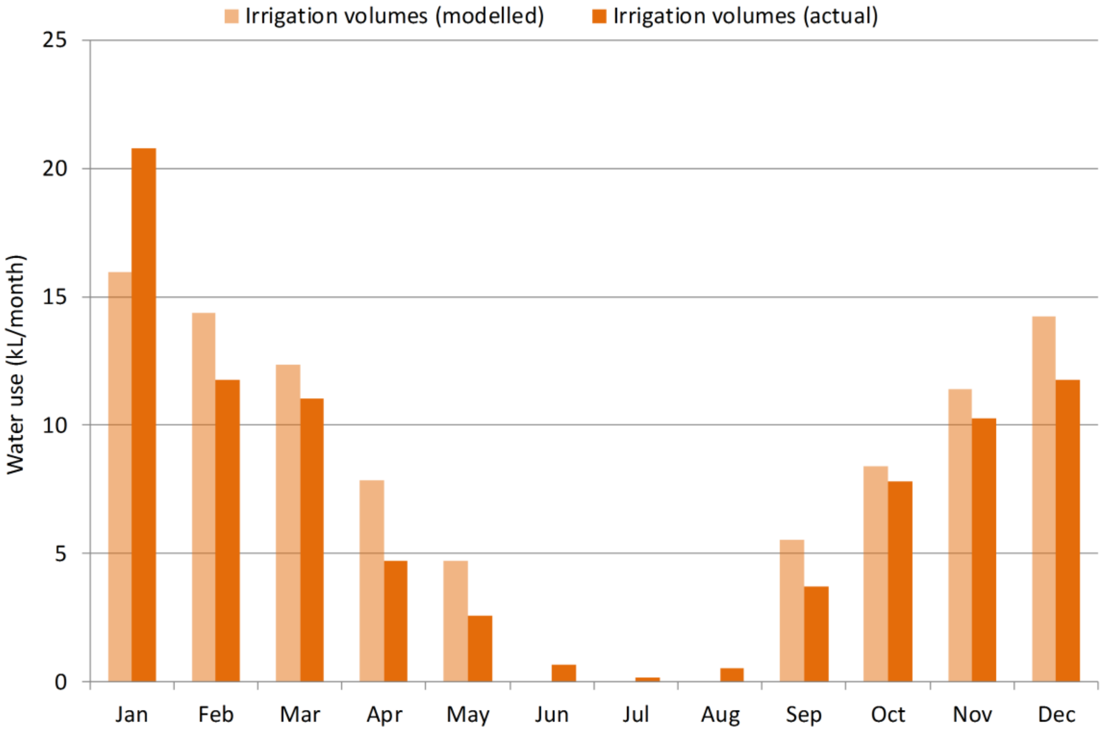


Figure 32: Comparison of modelled irrigation demand versus actual usage.

ASSUMPTIONS & QUALIFIERS

Irrigation volumes (sourced from the GndW bore) were logged across a 12-month period, from 1 January to 31 December 2015. As described above under the *Assumptions and Qualifiers* for Section 6.7.1, the GndW bore supply services two properties (shared strata bore) and the meter captures the total volume for both properties. A 60% allocation is assigned to CS3 based on the balance of irrigated area.

6.7.5 RAINWATER VOLUMES – ACTUAL VS MODELLING

Figure 33 shows the RW compared to MW use for internal house demands for CS3 by month, as well as the tank volume across the year. It can be seen that RW is used for ten months of the year, making up 73% of the indoor water supply. Whilst not directly related to MW savings in the garden (unlike CS1 and CS2 where internal RW for non-potable use offsets MW use in the garden), the results show the impact that RW harvesting can make in reducing household MW use. This is discussed further in the following chapter.

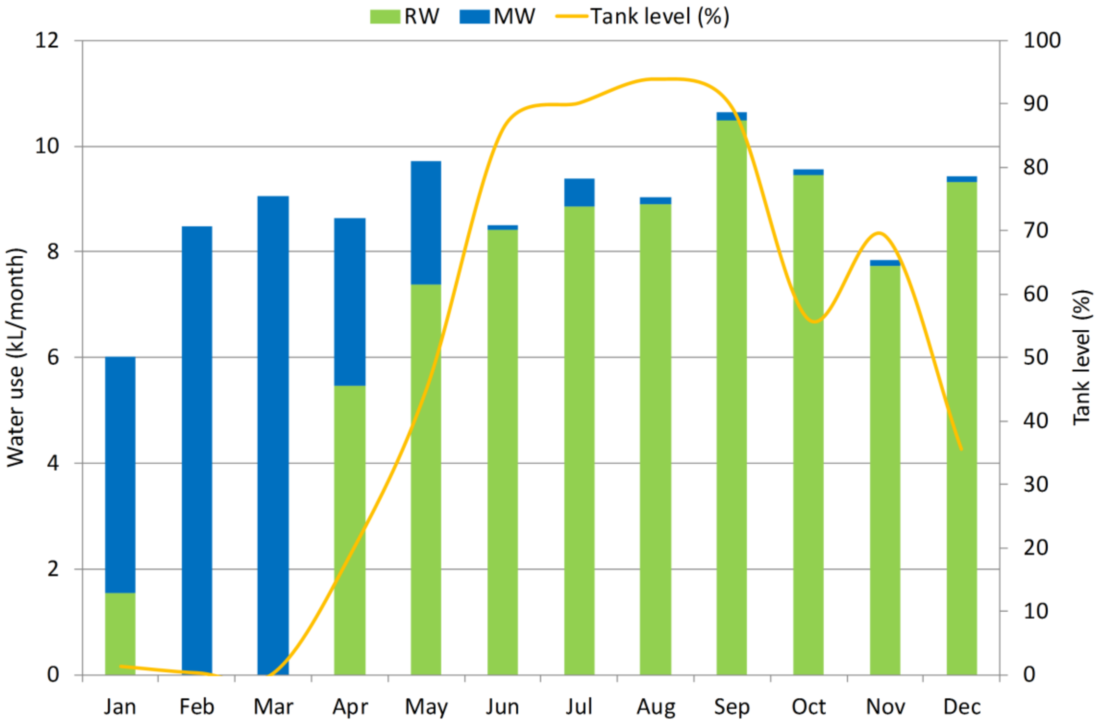


Figure 33: Rainwater versus mains water use for internal demands by month at CS3.

Figure 34 presents the local rainfall during the study period (667mm) with the recent average of 706mm (1996–2010) used for the modelling by month. This represents a 6% reduction in the figures used for the modelling, however the actual monthly rainfall values were fairly consistent with the estimated values for all months of the year.

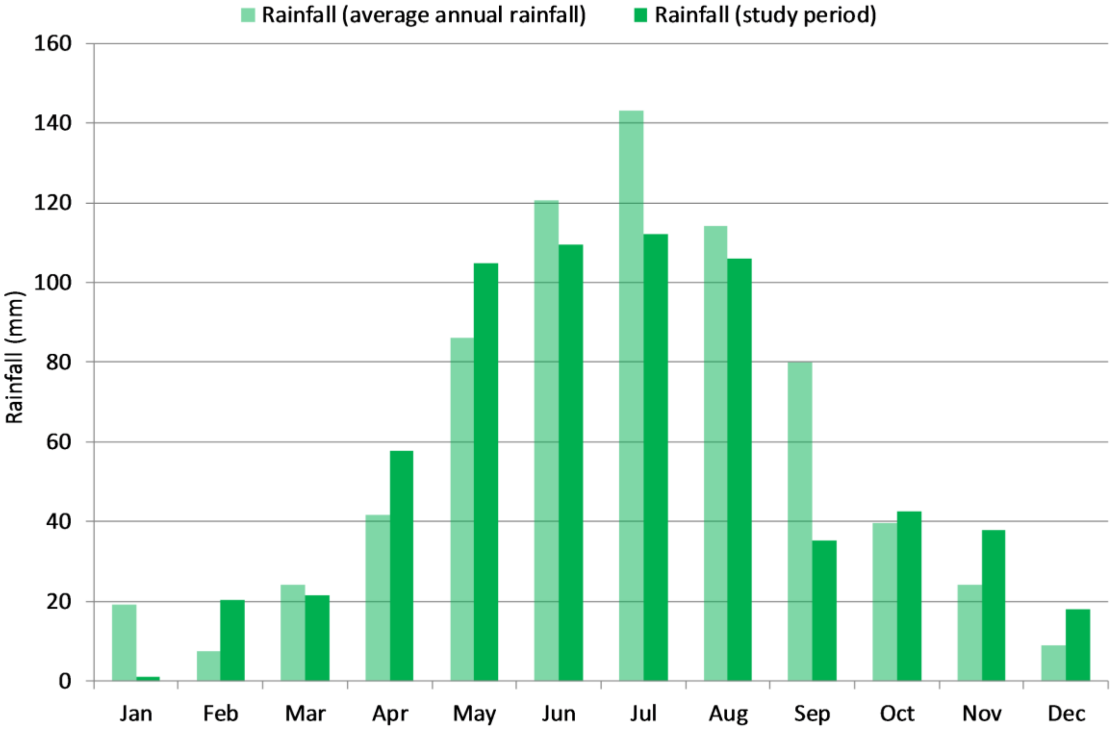


Figure 34: Comparison of rainfall during the study period (2015) and recent average (1996–2010) at case study 3 (using data from Bureau of Meteorology Station 009215).

ASSUMPTIONS & QUALIFIERS

RW volumes were metered and RW tank levels were monitored consistently between 1 January and 31 December 2015 and the results presented reflects the data logged.

The rainfall data presented in Figure 34 was sourced from the Bureau of Meteorology station in Swanbourne.

6.7.6 ENERGY INTENSITY OF WATER SOURCES

Figure 35 presents the energy intensity of the water sources at the CS3, in comparison to MW supplied via the Integrated Water Supply Scheme (IWSS), as well as the estimated energy cost for large-scale seawater desalination in Perth (Water Corporation, 2015). The graph shows that GW and GndW have a lower energy intensity than the MW supplied via the IWSS (which is made up of groundwater, surface water and seawater desalination sources), with a reduction of 62% for GW and 56% for GndW extraction. The comparatively high energy intensity of RW compared to all other sources is due to the UV lamp for disinfection).

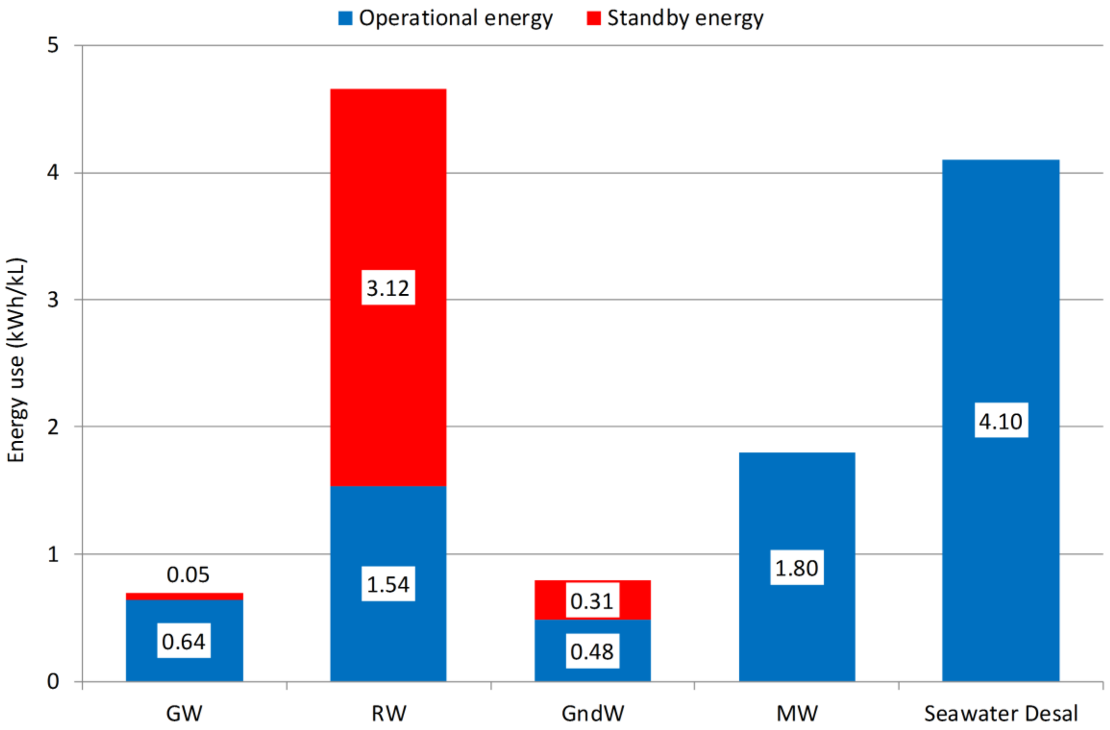


Figure 35: Energy intensity of each of the water sources at case study 3, compared with the IWSS and seawater desalination.

Note: Standby energy incorporates any non-pumping duty energy requirements, including UV disinfection lamp for RW.

Figure 36 shows the proportion of household energy usage attributed to supplying water from the various sources at CS3, as part of an energy-efficient home, compared with local average household energy use. The amount of energy generated via rooftop solar (3kW) is also shown. Whilst the combined annual energy requirement of the GW, GndW and RW systems (517kWh) make up 17% of the total household energy use (3.1MWh), it would only represent 8% of a typical household load (Australian Energy Regulator, 2016). Additionally, all of the household energy use (3.1MWh) is comfortably offset by solar power generation (5.2MWh) for all months, except in the winter month of July where it matches the load.

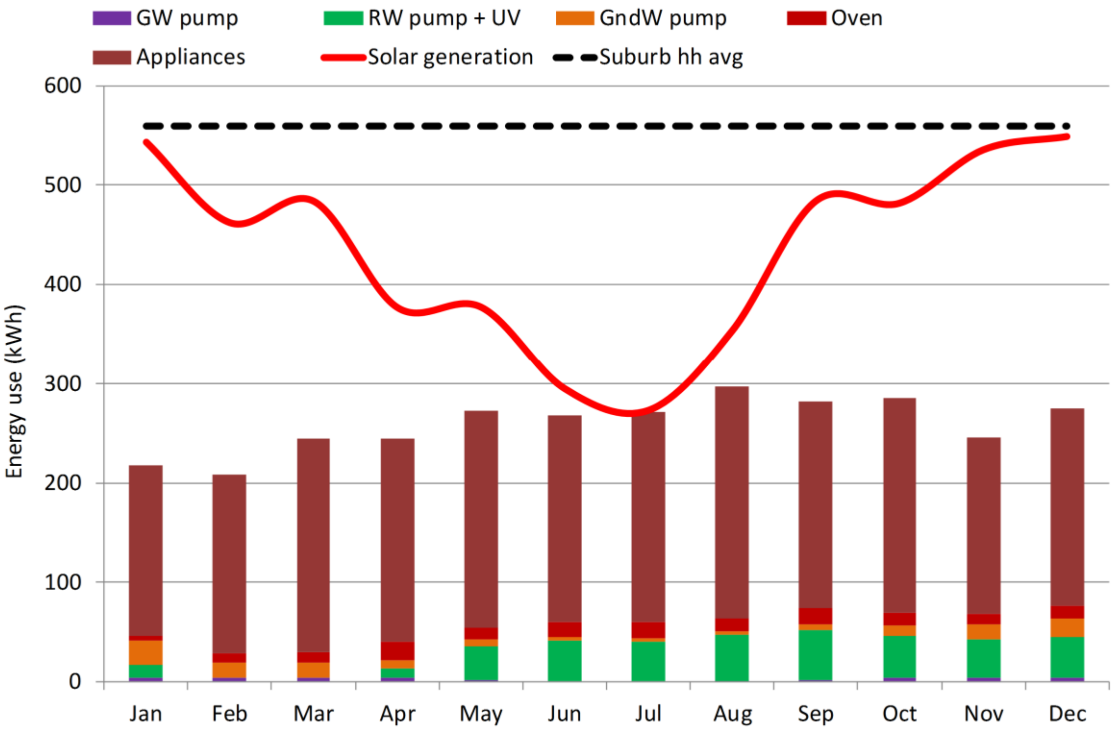


Figure 36: Proportion of household electricity used to supply water from on-site sources at case study 3.

ASSUMPTIONS & QUALIFIERS

The GW volumes used to establish the energy intensity values in Figure 35 were based on the 84-day sampling period between 1 October and 24 December 2015, as described in Section 6.7.2. The GW electricity usage for this graph was also taken from that range. To be consistent, the same time range was applied to RW and GndW volumes to determine the electricity usage for the RW pump and GndW pump respectively.

The GW pump data presented in Figure 36 was also based on the 84-day sampling period and then annualised based on the number of months it was operational. All other data presented was logged between 1 January and 31 December 2015.

6.8 REFLECTIONS & LESSONS LEARNED

6.8.1 WATER SYSTEM EQUIPMENT PERFORMANCE

GREYWATER SYSTEM

The GW system performed well during the monitoring period with no malfunctions. As per CS2, the automatic filter back flushing largely eliminated the need for manual filter cleaning during regular operation, other than when the system was switched back on after the winter months (June–August) when GW was not required for the garden.

GROUNDWATER WATER BORE

The GndW bore system, including pump and controls, performed well during the monitoring period with no malfunctions.

IRRIGATION SYSTEM

The irrigation system performed well during the monitoring period with no malfunctions. The web-based interface, which allows for remote access to the controller, enabled top-up watering, and system shut-off enabled close user control (by the author) during periods when pre-set automation would likely have resulted in over or under watering. The controller also had a rain shut-off sensor installed to limit irrigation events during heavy rain events, however the system would typically be switched off during these periods.

RAINWATER SYSTEM

The RW system performed well during the monitoring period with no malfunctions.

6.8.2 MONITORING METHODOLOGY & RELIABILITY OF DATA

CS3 represents the most comprehensive monitoring of the three case studies. The metering of all water sources, as well as pump energy usage for the entire monitoring, enabled detailed assessment of both individual system performance, as well as overall water use figures without the need for data extrapolation (with the exception of GW volumes, as identified in Section 6.7.2), with reliability of the data attributed to quality of equipment, installation and ongoing management based on the experience gained from by author during CS1 and CS2.

The use of this data for real-time feedback to householders via a data dashboard was also seen as a useful management tool enabling ease of confirmation that monitoring equipment was operational, as well as helping to inform occupant decisions relating to water and energy use.

6.8.3 ALTERNATE WATER SYSTEM COSTS & PAYBACK PERIODS

GREYWATER

Table 30 presents the supply, installation and operational costs for the GW system at CS3. The cost build-up is shown by item, along with the estimated life span / replacement intervals and annualised costs. The total cost over life of the system is estimated to be $6,887 assuming an operational life of 20 years (Memon *et al*., 2005). This equates to $344 per year when annualised over this period, or $7.38/kL based on the 47kL of GW supplied by the system. Using a figure of $1.78 per kL[1] for MW suggests a payback period of 83 years, which is well beyond the expected life span of the system. The system operating costs including electricity, plus annualised pump, blower, controller and filter replacement is approximately $155 per annum.

Table 30: Greywater system costs for case study 3.

Greywater system items	**Capital cost ($)**	**Estimated life/ replacement intervals (Yrs)**	**Annualised cost ($)**	**Life of system costs ($)**	**NPV ($)** Discount rate: 7%
GW system - initial supply and install	2300	20	115	2300	2300
Hired labor for GW ready plumbing	1500	20	75	1500	1500
GW pump replacement	350	7.5	47	933	688
Blower replacement	300	7.5	40	800	589
Controller replacement	250	7.5	33	667	491
Filter replacement	50	7.5	7	133	98
Labour	150	7.5	20	400	295
Maintenance (by user)	0	NA	0	0	0
Power per annum (0.69kWhr/kL) @ $0.26/kW[2]	8	20	8	154	82
GW system - cost over life	4908	20	344	6887	6042

[1] The unit cost of water is based on local supply charges for MW taking into account the tariff tiers relative to the total property water consumption (Water Corporation, 2016).

[2] Local supply flat tariff rate (Synergy, 2016).

The GW system costs are for the supply and install of the GDD only, plus all associated plumbing, but does not include the dripline irrigation component as this cost would be covered in a typical business as usual (BAU) irrigation installation (which is around $10/m^2 for dripline).

The cost of the GW system is within the typical range for GDDs of this type and functionality (ATA, 2009).

GROUNDWATER BORE SYSTEM

Table 31 presents the supply, installation and operational costs for the GndW Bore system at CS3. The cost build-up is shown by item, along with the estimated life span / replacement interval and annualised costs. The total cost over life of the system is estimated to be $3,352, assuming an operational life of 20 years (Khan *et al.*, 2008). This equates to $168 per year when annualised over this period, or $1.95/kL based on the 86kL of GW supplied by the system. Using the figure of $1.78 per kL for MW suggests a payback period of 22 years, which is just outside the expected life span of the system. The system operating costs including electricity, plus annualised pump, replacement is approximately $43 per annum.

Table 31: Groundwater bore system costs for case study 3.

Groundwater system items	**Capital Cost ($)**	**Estimated life/ replacement intervals (Yrs)**	**Annualised Cost ($)**	**Life of System Costs ($)**	**NPV ($)** Discount rate: 7%
Bore - supply & install (50%)	1750	20	88	1750	1750
Bore - pump & controls (50%)	750	20	38	750	750
Pump replacement (50%)	250	10	25	500	377
Maintenance (by user)	0	NA	0	0	0
Power per anum (0.79kWhr/kL) @ $0.26/kW	18	20	18	352	187
Bore - cost over life	2768	20	168	3352	3064

The bore system costs are for the supply and install of the bore, pump and controls only, plus all associated electrical works, but does not include the irrigation component as this would be installed in a BAU irrigation installation.

These bore system supply and installation costs are in line with typical industry prices (Marsden Jacob Associates, 2009).

RAINWATER SYSTEM

Table 32 presents the supply, installation and operational costs for the RW system at CS3. The cost build-up is shown by item, along with the estimated life span / replacement intervals and annualised costs. The total cost over life of the system is estimated to be $22,290, assuming an operational life of 20 years (Gurung *et al.*, 2012). This equates to $1,115 per year when annualised over this period, or $14.29/kL based on the 78kL of RW supplied by the system. Using the figure of $1.78 per kL for MW suggests a payback period of 161 years, which is well beyond the expected life span of the system. The system operating costs including electricity, plus annualised pump, MWBV, filter and UV lamp replacement is approximately $395 per annum.

Table 32: Rainwater system costs for case study 3.

Rainwater system items	**Capital cost ($)**	**Estimated life/ replacement intervals (Yrs)**	**Annualised cost ($)**	**Life of system costs ($)**	**NPV ($)** Discount rate: 7%
RW Tank	4200	20	210	4200	4200
RW Pump, MWBV, filtration, & disinfection unit	5000	20	250	5000	5000
RW Pressure Tank	200	20	10	200	200
Hired labour for RW plumbing	5000	20	250	5000	5000
RW pump replacement	500	10	50	1000	754
MWBV replacement	500	10	50	1000	754
Maintenance (Filter & UV lamp replacement)	200	1	200	4000	2119
Power per annum (4.66kWhr/kL) @ $0.26/kW	95	20	95	1890	1001
RW system - cost over life	15695	20	1115	22290	19028

The RW system costs are for the tank, pump, mains water backup valve (MWBV) and associated roof drainage and RW supply modifications and do not include original roof guttering costs, which are also required in a BAU roof drainage scenario.

The supply and installation costs of a RW tank at CS3 are higher than those referenced in the literature for a similar-sized system, such as Coombes *et al.* (2003) and Gurung *et al.* (2012), which can be attributed to the size of the tank (18kL), the extent of additional roof plumbing required to capture the entire roof area via a ‘wet feed’ drainage arrangement, as well as the inclusion of a UV disinfection system due to the RW being used for potable purposes.

The limitations of using a payback model based on MW cost per kilolitre savings is discussed in Chapter 7 (Discussion) and Chapter 8 (Conclusion).

CHAPTER 7: DISCUSSION

7.1 CHAPTER INTRODUCTION

This chapter addresses the research questions put forward in Chapter 1 by providing a synthesis of the findings from the three case studies presented in Chapters 4–6, as well as drawing on findings from the literature reviewed in Chapter 2.

7.2 RESPONSE TO RESEARCH QUESTIONS

Research Question 1: What constitutes a ‘sustainable urban garden’?

The Sustainable Urban Gardening (SUG) framework presented in Chapter 2 presents a definition for ‘sustainable urban gardening’ based on clear sustainability goals supported by the literature reviewed. The case studies presented in Chapters 4–6 of this thesis demonstrate working examples of sustainable urban gardens based on the SUG framework, and these case studies are evidenced by landscape plans and accompanying photographs which illustrate a creative interpretation of the SUG goals and demonstrate how the desired outcomes have been achieved.

The implementation of the design and operational considerations of the SUG framework are demonstrated by the extensive coverage each case study site received on national television through the Australian Broadcasting Corporation’s program *Gardening Australia*. Each of the case study sites was documented throughout the construction and establishment phases, resulting in 117 stories aired over a ten-year period. Links to the story transcripts and episodes are provided in Appendix 1.

Research Question 2: What are the opportunities for alternative water sources at the lot-scale to support sustainable urban gardens and reduce reliance on mains water? Specifically:

A. Is lot-scale greywater reuse an effective way to reduce mains water use in sustainable urban gardens?

The greywater (GW) volumes applied in case studies (CS) 1, 2 and 3 during the study periods were 64.8L, 40.1L and 46.7kL respectively, but this does not equate to direct mains water (MW) substitution as GW application often exceeded hydrozone water demand (HzWD). The values of interest are the GW HzWD volumes which are presented in Table 33, along with the volumes of GW matched to those demands (i.e. actual MW substitution). The proportion that this contributes to the overall Garden Water Requirement (GWR) is also provided.

Table 33: Impact of greywater in reducing mains water demand for each case study site.

Case study site	Total GW applied (kL)	GW HzWD (kL)	Actual MW substitution (kL)	% of GWR
CS1	64.8	31.6	31.6	59.1
CS2	40.1	46.8	35.5	53.7
CS3	46.7	46.8	39.4	27.8

The figures show that annual MW savings of 59.1%, 53.7% and 27.8% can be attributed to GW diversion in CS1, CS2 and CS3 respectively. In response to the research question, it can be seen that the reuse of GW via greywater diversion devices (GDD) has effectively contributed to MW savings, but it is a smaller proportion than the volumes applied. It should be noted, however, that the MW savings demonstrated by this calculation method are conservative, as the comparison assumes that the irrigation scheduling (if supplied by MW) would have been accurately estimated and adjusted monthly with changing seasonal evapotranspiration rates, in line with the methodology presented in Chapter 3, Section 3.3.1. Perhaps it is more reasonable to assume that irrigation systems would be turned on in spring and either left running at a set rate through the seasons, until being switched off come winter, or potentially adjusted up at the transition from spring to summer and then down from summer to autumn to reflect changing plant water demand. Either way, it would result in higher MW consumption than shown in Table 33. Whilst these values are difficult to quantify, provided that HzWD is met by the GDD (thus negating the need for MW irrigation in that hydrozone (Hz)), further MW savings would be achieved.

B. Does lot-scale rainwater harvesting have a role to play in reducing the reliance on MW for meeting the water demand of sustainable urban gardens in summer-dry climates?

Rainwater (RW) was used for garden watering in CS1 (irrigation and garden tap) and CS2 (garden tap), where the volume of RW used during the study periods was 12.6kL and 1.8kL respectively. To answer the research question, we need to establish how much of that RW is actually substituting MW, in a similar way to what was done for GW in addressing Research Question 2A. Here the value of interest is the sum of HzWDs serviced by RW during the irrigation period when RW is available, plus the volume used via garden taps.

The volume of RW used via garden tap can be considered genuine MW savings, because, unlike automatic irrigation systems which may be left to over-run on an automatic program once activated, the operation of a tap is based on a conscious decision and manual action. It is reasonable to assume that whether that water is actually required for meeting GWR, it is being used nonetheless and is therefore substituting MW.

Table 34 presents the RW volumes applied to CS1 and CS2, along with the sum of HzWD serviced by RW (CS1) and the available RW matched to those demands (actual MW substitution). The contribution of RW towards meeting HzWD, plus overall GWR is provided, along with proportion of RW used for irrigation compared with toilet and washing machine use.

Table 34: Contribution of rainwater to garden water demand and other purposes for case studies 1 and 2.

Case study site	**Total RW applied** (kL)	**∑ HzWD serviced by RW** (kL)	**Actual MW substitution** (kL)	**% of ∑ HzWD serviced by RW**	**% of GWR**	**% of RW use**
CS1 Irrigation & garden tap	12.6	21.9	10.4	47.5	19.4	34.9
CS2 Garden tap only	1.8	NA	1.8	NA	2.7	7.4

It can be seen that RW has substituted 10.4L and 1.8kL of MW at CS1 and CS2 respectively, which represents 19.4% and 2.7% of the GWR, 47.5% of the CS1 HzWD serviced by RW, and 34.9% and 7.4% of the overall RW demand.

In CS1 RW makes a reasonable proportional contribution (47.5%) to the HzWD (serviced by RW) but this is due to the relatively small area being irrigated (14m^2). The contribution soon drops away to 19.4% of GWR (and 34.9% of total RW use) as the irrigation area increases to include the GW Hz. This suggests that in summer-dry climates, RW is better matched to indoor demands where it can be utilised during winter months when it is available. This view is supported by Gray (2002) and Loux *et al.* (2012).

The modelled RW yields for different storage scenarios for the case study sites is summarised in Table 35 below, where the limited impact of RW harvesting on MW demand in Perth’s summer-dry climate is evidenced by the decreasing return in upsizing of storage. Most of the yield is obtained from the initial storage volumes during the winter months when most rain events occur. CS1 yield only increases by 9.6kL from 36kL with a 2.5kL tank, to 45.9kL with a 10kL tank, i.e. a 21% yield increase with a 400% storage volume increase. Similar trends can be seen for CS2 and CS3 despite their different configurations, including catchment size and demands.

Table 35: Rainwater yield for each case study sites for various storage sizing scenarios.

Case study sites	**Actual RW used**	**Modelled application**								
		2.5kL	3.5kL	5kL	7.5kL	10kL	15kL	18kL	25kl	100kL
CS1	32.0	36.3	38.3	40.3	43.3	45.9	–	–	–	–
CS2	24.2	28.1	29.5	31.1	33.5	35.4	–	–	–	–
CS3	77.6	–	–	–	–	87.7	93.3	96.4	103.5	134.4

C. What role do residential groundwater bores play in reducing MW demand when used in conjunction with GW and RW systems in sustainable urban gardens?

As identified in Chapter 2, Section 2.4.3, the use of groundwater (GndW) for residential garden irrigation in the Perth Metropolitan region is recognised as reducing demand on MW supplies, with annual consumption of GndW estimated in the vicinity of 73GL, at an average of 440kL per property (Department of Water, 2011). As with determining the impact of GW and RW on MW reduction, this figure should not be translated into direct MW savings as it is highly likely that significant over-irrigation is occurring, given the high volume presented and when compared to the GndW use volumes recorded at CS3.

GndW was utilised in CS3 for garden irrigation and outdoor taps, with an annual usage of 85.8kL, accounting for 72.2% of total annual GWR. Its inclusion allowed for a significant increase in irrigated areas that supported additional food production and play areas (including lawn), where GW and RW volumes would have been insufficient (based on learnings from CS1 and CS2) or of unsuitable quality (Department of Health, 2010). Table 36 presents the difference in irrigated area by Hz across all case study sites, which shows CS3 having a combined area of 59.5m^2 of intensive irrigated food production and lawn (outside of the GWHz), compared to 14m^2 and 16m^2 for CS1 and CS2 respectively.

Table 36: Garden areas by hydrozone for each case study site.

Case study site	Mixed perennials (GW)		Vegetables		Fruit trees		Productive pots		Lawn		Native garden	
	m^2	%	m^2	%	m^2	%	m^2	%	m^2	%	m^2	%
CS1	27	40.3	8	11.9	–	–	6	9.0	–	–	26	38.9
CS2	40.0	11.8	4.0	1.2	–	–	2.0	.01	10.0	17.9	284	83.5
CS3	40.0	33.5	20.0	16.7	14.5	12.1	5.0	4.2	20.0	16.7	20.0	16.7

D. What are the MW savings from integrating a suite of alternative water sources, along with efficient irrigation practices as part of a water-sensitive landscape design approach to sustainable urban gardens?

CS1, CS2 and CS3 demonstrated MW reduction of 42%, 72% and 92% respectively on a per person basis when compared to the Perth average, whilst achieving a high level of garden amenity, productivity and liveability, as demonstrated in Chapters 4–6. These savings are significant; however, to address the research question, a closer examination of the contribution that GW, RW and GndW played in meeting GWR is required – including the extent to which using RW for indoor non-potable purposes offset MW use for irrigation in CS1 and CS2 – as well as an analysis of the proportion of irrigated landscape relative to MW use at each case study site.

Table 37 summarises the GW, RW and GndW contribution to reducing MW at each of the case study sites. For CS1 and CS2, GW was the biggest contributor to direct MW reduction (59.1% and 53.7% respectively). Whilst the direct contribution of RW towards GWR is relatively low (19.4% and 2.7% respectively), when the internal RW volumes supplying toilet and washing machine are included in line with the MWNG concept with 19.5kL used at CS1 and 22.4kL used at CS2, the contribution of RW becomes much more significant. For CS3, where RW is used exclusively for internal purposes (servicing all demands when available), MW substitution is comprised of GW and GndW to the value of 100% (27.8% GW and 72.2% GndW).

Table 37: Contribution of greywater, rainwater and groundwater to mains water savings.

Case study site	MW substituted by GW %	MW substituted by RW %	MW substituted by GndW %	Outdoor MW offset %
CS1	59.1	19.4	–	62%
CS2	53.7	2.7	–	105%
CS3	27.8	–	72.2	NA

Table 38 presents the total planted areas for each of the case studies along with the proportion of planted area that is irrigated. Total household water use (all sources) and MW use (total household and outdoor only) are provided for comparison, along with the reduction in Perth average household outdoor MW use and Perth average total MW use (per person per year).

Table 38: Volume of mains water used against size of property and irrigated areas for each case study site.

Case study site	Planted area (inc. verge) (m$^{2)}$	Proportion of planted area irrigated (%)	Total hh water used (all sources) (kL/yr)	Total hh MW used (kL/yr)	MW used for garden purposes (kL/yr)	Red. in garden MW use from Perth avg (hh/yr) (%)	Red. in hh MW use from Perth avg (p/yr) (%)
CS1	67	61.2	270.4	173.6	32	72	42
CS2	340	16.5	148.9	84.6	21	82	72
CS3	120	100	233.9	28.8	0	100	92

CS1 recorded the highest household water volumes (three persons) for both MW (173.6kL/yr) and all sources combined (270.4kL/yr), despite having the smallest irrigation area. As outlined in Chapter 4, Section 4.7, this is largely due to high internal water use (showers), which has also resulted in high GW volumes, and can be attributed to occupant behaviour. Irrigation volumes were also higher than expected, again due to occupant management. Despite this, CS1 demonstrates a 72% reduction in outdoor MW use compared to the Perth average whilst enabling 62% (67m^2) of planted areas to be adequately irrigated.

CS2 recorded the lowest household water volumes (three persons) for all sources. Despite having the largest planted area (340m^2), only 16.5% of this was irrigated, of which the majority was serviced by GW. The result is an 82% reduction in garden MW use compared to the Perth average.

CS3 sustained the largest area of irrigated garden (120m^2), with full substitution of MW with a combination of GW (27.8%) and GndW (72.2%). The inclusion of RW to service all internal demands (when available) has meant that MW consumption on a per person basis is only 8% of the Perth average.

The inclusion of GndW in CS3 enabled a significant increase in irrigated areas that were used for vegetables, fruit trees and lawn (as demonstrated in Table 36), contributing significantly to the food production capacity of the garden, and subsequently the health and wellbeing of the householders.

Unlike GW and RW, in areas where GndW is available and suitable for use, its supply is often not immediately physically constrained. Its overuse contributes to a gradual depletion of the aquifer and a potential decrease in water quality (e.g. saltwater intrusion), which can impact on surrounding GndW dependent ecosystems (Harrington and Cook, 2014). Its sustainable use needs to be informed by a threshold to prevent over extraction, as well as fair and equitable use of a common resource (i.e. in the case of Perth (and elsewhere) where there is no financial cost on the consumer for its use). The sustainable extraction limits (GndW extraction ≤ GndW Infiltration) set by the Mains Water Neutral Gardening (MWNG) water balance model provide such a threshold. As demonstrated in Chapter 6, Section 6.7.3, CS1 annual GndW extraction of 86kL was well within the yield limits of 199kL. If GW reuse had not been included, this would have placed an additional 46.7kL demand on the aquifer (as shown in Table 33), and whilst this combined value of 132.5kL is still within the threshold, the buffer allows for further rainfall decline as forecasted (Bureau of Meteorology, 2015) and/or some capacity for additional irrigation usage for future garden development.

Research Question 3: What is the significance of such an approach and what are the broader applications and barriers to adoption?

Reducing MW use by restricting sprinkler irrigation to rostered days (or banning irrigation altogether) is a proven mechanism to reduce water use (Water Corporation, 2010), but it also limits opportunity for the inclusion of some SUG design elements and garden activities (such as vegetable growing) that are conducive with health, wellbeing and sustainable urban gardening more broadly.

The MWNG model on the other hand sets limits to water consumption without compromising gardening opportunities or performance. By providing a rational and transparent water budget that is intrinsically linked to a site, household occupancy, technology choice and landscape design, it provides the necessary guidance by which to design and develop a garden based on sustainable water management. In other words, MWNG is an enabling approach, rather than a restrictive one.

Theoretically, the effective deployment of MWNG should result in greater water use reductions than what can be achieved via restrictions. In fact, the water use of a household with a garden based on MWNG can be expected to have similar (or less) annual MW use than a household with no garden (or garden water use), given that any MW used to meet GWR would be within an allowance that can be 'paid back' during rainy periods by substituting indoor non-potable purposes, as outlined in Chapter 3, Section 3.2.

The MW reductions demonstrated by case studies 1, 2 and 3 are evidence of the effectiveness of the MWNG model, given that the 42%, 72% and 92% savings achieved across the three sites respectively are comparable to the Perth average where Stage Four water restrictions (which limit garden watering with MW to two days per week) have been in place since 2001. And although CS1 didn't achieve MWNG status during the trial period (for reasons previously outlined), the testing of the model via the three case studies presented in Chapters 4–6 show it to be practical and robust. Furthermore, operational energy data collected from CS3 demonstrated that GW (0.7kWhr/kL), RW (excluding UV disinfection lamp) (1.5kWhr/kL) and GndW (0.8kWhr/kL) can be supplied at a lower energy intensity than MW (1.8kWhr/kL) and well below that of seawater desalination (4.1kWhr/kL) which is the main source of new water supplying the IWSS (Water Corporation 2009).

The MWNG model also informs more effective deployment of specific alternative water sources, for example, by anticipating the likely shortfalls of GW volumes in relation to HzWD, matching RW availability with real-time demand, and sizing Hzs serviced by GndW in relation to sustainable yield determined by site catchment recharge.

The literature reviewed in Chapter 2, Sections 2.3–2.4, identified a number of well recognised barriers to the adoption to GW and RW systems, including cost, logistics (for retrofitting in particular), regulatory restrictions, and lack of industry capacity (Ng, 2004; Alternative Technology Association, 2009 Byrne *et al.*, 2008; Evans, 2009). The cost barrier in particular is reflected in the relatively low uptake of these systems, except where they have been mandated or incentivised.

Whilst a detailed cost-benefit analysis is outside the scope of this thesis, it is important to note that in all three case studies, the payback periods for the GW and RW systems on a cost per kilolitre basis were well beyond the expected lifespan of the equipment. Whilst this was in part due to the cost of equipment and the nature of the installations as described in Sections 4.4, 5.4 and 6.4, the long payback periods were also the result of the low volumes of water yielded due to the efficient use of water. Similarly, the combined annual operating costs for the alternate water systems (excluding initial capital costs for installation) were approximately $335 for CS1 (GW and RW), $270 for CS2 (GW and

RW) and $593 for CS3 (GW, RW and GndW), whereas the cost of MW to supply the equivalent volume would have been $176, $102 and $396 for CS 1, 2 and 3 respectively.

Perversely, if more water had been consumed (assuming its availability in the case of RW), payback periods, and comparative operating costs would have been more attractive, by means of both volumetric usage and the corresponding tiered tariff rates used in the calculations. Clearly other enablers are required to support the greater uptake of these lot-scale water sources given the limitations of using a financial payback model alone.

One potential strategy to overcome the cost barrier, without the need for financial incentives, would be to exempt from water restrictions those households who implement MWNG. This would be a cost neutral exercise for government and provide incentive to householders to outlay the necessary capital costs for equipment and design on the grounds that they have security of supply to sustain their garden. This approach would have particular merit in regions that are frequently (or continually) subjected to MW restrictions and where increased restrictions (including total MW irrigation bans) are a genuine threat.

CHAPTER 8: CONCLUSION

8.1 CHAPTER INTRODUCTION

This chapter concludes this thesis by providing a succinct summary of how the Aims and Objectives of this study, outlined in Section 1.2 of Chapter 1, have been addressed. Opportunities for further work following this body of research are also identified.

8.2 STUDY AIMS & OBJECTIVES ADDRESSED

OBJECTIVE 1: *Establish a conceptual framework for 'sustainable urban gardens' as the basis for informing a landscape design and determining a responsive landscape water budget.*

Response: An original conceptual framework for Sustainable Urban Gardening (SUG) has been developed as part of this study and summarised in Table 1. It is supported by the academic, technical and industry literature reviewed in Chapter 2 and its practical application has been demonstrated via three case study gardens extensively documented in Chapters 4–6. The SUG framework has also been documented and showcased via two books and 117 stories broadcast on national television (refer Appendix 1).

OBJECTIVE 2: *Identify the role, opportunities and constraints of lot-scale alternative water sources in supporting sustainable urban gardens.*

Response: The challenges facing large-scale centralised approaches to water service delivery in the face of growing urban populations and a changing climate with increasing rainfall variability were articulated in Chapter 2, Section 2.3 and supported by the literature reviewed. Emerging approaches such as Integrated Urban Water Management and Water Sensitive Urban Design are providing alternative approaches to centralised water systems and enable better utilisation of alternative water resources for local fit-for-purpose uses. Lot-scale sources such as greywater (GW), rainwater (RW) and groundwater (GndW) provide a relatively accessible transition to a 'third-pipe' model at the residential scale as described in Chapter 2, Section 2.4 and supported by the literature. These sources have the potential to provide reliable supply at a comparable or lower energy intensity than conventional mains water (MW) supply. They are also unburdened by restrictions. Irrigation restrictions, a common mechanism to limit demand on MW, can significantly impact garden performance and thereby impact SUG goals such as 'Food Production' and 'Health and Wellbeing of Householders'. A major constraint of lot-scale water systems in relation to SUG is the ability to temporally match available volumes with Garden Water Requirements (GWR), in the case of GW and RW, and sustainable yield of GndW, as identified in Chapter 2, Sections 2.4–2.5, as well as Chapter 3, Section 3.3. In addition to this constraint, a number of barriers exist limiting further uptake of lot-scale water systems including regulatory challenges, limitations in industry capacity and cost. As constraints on traditional supplies become more severe, these barriers will likely be overcome by attrition.

OBJECTIVE 3: *Develop an integrated water system model for sustainable urban gardening to meet landscape water demand whilst reducing reliance on MW.*

Response: Mains Water Neutral Gardening (MWNG) is a new model developed as part of this study which aims to reduce reliance on MW without compromising landscape opportunities and plant performance. It draws on the findings developed from a review of the literature identified in Chapter 2. It goes beyond the existing work done by others by fully integrating available lot-scale water sources, such as GW, RW and GndW, with efficient irrigation practices and local environmental conditions to establish holistic water budgets that are capable of meeting GWR as part of a water-sensitive landscape design. The MWNG model principles and methodology for its application have been detailed in Chapter 3 and their testing described in Chapters 4–6.

OBJECTIVE 4: *Quantify and test the robustness of the water system model through the monitoring and analysis of suitable case study sites.*

Response: The MWNG model was tested via three case study sites that were designed and built as part of this study, and which were all based on both the SUG framework and MWMG principles. The case studies are extensively detailed in Chapters 4–6, including alternative water system infrastructure, design modelling and actual performance results from the operation of the established gardens. Two of the three case studies (CS2 and CS3) were successfully operated with their MWNG water budget, with CS1 exceeding irrigation use due to poor irrigation management during the trial period. Nonetheless CS1 still demonstrated a 42% reduction in MW use compared to the Perth average. CS2 and CS3 demonstrated a 72% and 92% reduction respectively.

8.3 CLOSING SUMMARY & OPPORTUNITIES FOR FURTHER WORK

The research described in this thesis has demonstrated how sustainable urban gardens can be successfully established and sustained in MW-constrained environments through the considered integration of lot-scale alternative water systems with appropriate landscape design. The sustainable urban garden (SUG) framework presented in this thesis provided a useful means of both guiding the design of each of the case study gardens, plus communicating their sustainability merits. Further work could be undertaken on the framework through the inclusion of quantifiable performance indicators, or other metric-based criteria, thus strengthening its value as both a design and assessment tool. Numerous tools are available for the building and urban development industry, but none specifically for residential gardening.

The novel MWNG concept presented in this thesis was used to inform the site-specific sizing of water system infrastructure and landscape hydrozones based on estimated irrigation demand and household water use, resulting in MWNG status being achieved in two of the case study sites, and a significant reduction in MW use across all three. The model was a creative response to the unique challenges faced by Mediterranean (winter-wet, summer-dry) climates in comparison to other climate types that either experience summer rainfall, or those that experience rainfall more evenly throughout the year. It stands to reason that the MWNG concept would be transferable to other regions, with consideration given to different climate conditions (rainfall and evapotranspiration), soil types and groundwater availability, as well local regulations relating to the use of GW and RW. With further work, the spreadsheet–based tool used for the modelling and MWNG calculations for the case studies in this thesis could be refined into a more versatile tool for assessing the appropriateness of various alternative water supply options and calculating optimal system sizing and configuration.

The discussion of GW reuse in the three case studies presented in this thesis focused on the contribution of GW to landscape water demand via direct diversion due to both costs drivers and enabling regulations in Western Australia when compared to the use of treatment systems. Additionally, all three case studies had adequate garden space to meet the design loading requirements needed for installation approval, as the result of the property sizes and the sandy soil characteristics of the sites. The house occupants were also committed to using 'GW-friendly' detergents and cleaning products in an effort to minimise the impact on soil and garden health. In smaller gardens, or where soil type is less suitable for GW application (e.g. heavy, dispersive clays), greywater treatment may be more appropriate. Observationally, the plants performed well in the hydrozones being irrigated with untreated GW, noting that plants suited to GW were intentionally chosen for these areas and appropriate detergents and personal care products were used. Notwithstanding the above, there is limited information available in the literature on the long-term impacts on soil and plant health from ongoing application of GW, assuming suitable products and soil management practice are implemented, and it remains an important area for further research.

Reliable monitoring of relevant water sources and uses to track the 'mains water neutrality' of a garden is important to not only verify performance, but also help guide householders in how they use water in the house and garden. Access to real-time data via an easy to interpret dashboard display is likely to enhance this process, as experienced in CS3. Advances in remote metering technology for households and real-time data display systems are likely to see more cost-effective and accessible equipment come to market, but it is an area that is currently underdeveloped.

Further work on developing a verification process would likely be required if the MWNG model was to be used as the basis for an exemption to watering restrictions as identified in Section 7.2 in response to Research Question 3. The move towards smart metering and online billing begins to set the scene for the viability of online reporting and verification processes, and an opportunity exists to explore this more fully.

The focus of this research was on single residential lots, with the design responses, technology selection and governance arrangements appropriate for that scale of development. As cities continue to densify, both here in Australia and elsewhere around the world, the need for creative responses for the integration of local water management strategies and urban green will become ever more present. With this in mind, there exists an opportunity to apply both the SUG framework and the MWNG model at a range of scales, including building, cluster (co-housing), and even precinct scales. Whilst there is already substantial work being done in the area of improved water efficiency and fit-for-purpose water supply, as well as built environment sustainability frameworks at these scales, it is proposed that using the SUG framework and MWNG model to inform the integration of water system options and sustainable urban landscaping has substantial merit.

Finally, there exist a number of barriers limiting the uptake of lot-scale alternative water systems, with perhaps the obvious being cost. As identified in response to Section 7.2, Research Question 3, it is important that a comparative cost per kilolitre value is not the only metric used to determine the viability of alternative water sources when compared to a business as usual base case. Whilst there is significant work already being done on the development of systems-based approaches to capture the benefits of integrated approaches to urban water management, as outlined in Section 2.3.2 of this thesis, further work needs to be done to better account for the opportunity cost of ‘Big Water’ being unable to supply sufficient water for gardening purposes, and for this to be factored into the true costs of water service delivery.

INTENTIONALLY BLANK PAGE

REFERENCES

Alternative Technology Association (ATA), 2009. ATA Smart Water GW Project – Project Report, ATA, VIC, viewed 4 December 2016, http://www.ata.org.au/wp-content/projects/smartwater_final_report.pdf.

American National Standards Institute (ANSI), 2005. ATS 5200:460 Technical Specification for plumbing and Drainage Products – GW Diversion Device, ANSI, Washington DC.

Anda, M., Brennan, J. & Paskett, E., 2013. Combining Smart Metering Infrastructure and Behavioural Change for Residential Water Efficiency. *Water*, 40, no. 5, 66-72.

Anda, M., Mohamed, R. M. S. R., Dallas, M. K. & Ho, G., 2010. Decentralised Wastewater Treatment and Recycling in Urban Villages. *Water Practice and Technology*, 5, no. 3, 1-11.

Anderson, J., Boldrin, A., Christensen, T. & Scheutz, C., 2012. Home composting as an alternative treatment option for organic household waste in Denmark: An assessment using life cycle assessment-modelling. *Waste Management*, 32, 31-40.

Australian Building Codes Board (ABCB), 2013. ATS 5200 Technical Specification for Plumbing and Drainage – Procedures for Certification of Plumbing and Drainage Products, ABCB, Canberra.

Australian Building Codes Board (ABCB), 2015. National Construction Code – Building Code of Australia, Volume 2: Building Code of Australia Class 1 and Class 10 Buildings, Australian Federal & State Governments, Council of Australian Governments (COAG), ABCB, Canberra.

Australian Bureau of Statistics (ABS), 2006, *2068.0 – 2006 Census of Population and Housing, Perth (Major Statistical Region) – WA, 2006 Census Tables*, viewed 4 December 2016, http://www.abs.gov.au/websitedbs/d3310114.nsf/51c9a3d36edfd0dfca256acb00118404/074b029ae7f4f3c7ca25721300145003!OpenDocument.

Australian Bureau of Statistics (ABS), 2009, *4656.5 – Household Choices Related to Water and Energy – WA*, viewed 4 December 2016, http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/4656.5October%202009.

Australian Bureau of Statistics (ABS), 2011, *2901.0 – 2011 Census of Population and Housing Perth (Major Statistical Region) – WA, 2011 Census Tables*, viewed 4 December 2016, http://www.abs.gov.au/websitedbs/censushome.nsf/home/2011information?opendocument&navpos=310.

Australian Bureau of Statistics (ABS), 2013, *4602.0.55.003 – Environmental Issues: Water Use and Conservation – March 2013*, viewed 4 December 2016, http://www.abs.gov.au/ausstats/abs@.nsf/mf/4602.0.55.003?OpenDocument.

Australian Greenhouse Office (AGO), 2005. *Your Home Design for Lifestyle and the Future Manual*, vol. 3, Canberra, Australian Government, Australian Greenhouse Office (AGO).

Bach, P., Rauch, W., Mikkelsen, P., McCarthy, D. & Deletic, A., 2014. A critical review of integrated urban water modelling – Urban drainage and beyond. *Environmental Modelling and Software*, 54, 88-107.

Barron, O., Froend, R., Hodgson, G., Ali, R., Dawes, W., Davies, P. & McFarlane, D., 2014. Projected risks to groundwater-dependant terrestrial vegetation caused by changing climate and groundwater abstraction in the Central Perth Basin, Western Australia. *Hydrological Processes*, 28, no. 22, 5513-5529.

Barthel, S., Folke, C. & Colding, J., 2010. Social–ecological memory in urban gardens – Retaining the capacity for management of ecosystem services. *Global Environmental Change*, 20, 255-265.

Barton, A. & Argue, J., 2009. Integrated urban water management for residential areas: a reuse model. *Water Science and Technology*, 60, no. 3, 813-823.

Bates, B. C., Hope, P., Ryan, B., Smith, I. & Charles, S., 2008. Key findings from the Indian Ocean Climate Initiative and their impact on policy development in Australia. *Climate Change*, 89, no. 3, 339-354.

Beal, C., Stewart, R. A., Huang, T. & Rey, E., 2011. South East Queensland Residential End Use Study. *Journal of the Australian Water Association*, 38, no. 1, 80-84.

Beatley, T., 2007. *Biophilic Cities: Integrating Nature into Urban Design and Planning*, Washington DC, Island Press.

Beatley, T. & Newman, P., 2009. *Green Urbanism Down Under: Learning from Sustainable Communities in Australia*, Washington DC, Island Press.

Beatley, T., 2012. *Green urbanism: Learning from European cities*. Washington DC, Island Press.

Beatley, T. & Newman, P., 2013. Biophilic cities are sustainable, resilient cities. *Sustainability*, 5, no. 8, 3328-3345.

Beatley, T., 2013. New directions in green city building. In M. Achilles & D. Elzey (eds), *Environmental Sustainability in Transatlantic Perspective: A Multidisciplinary Approach*, UK, Palgrave MacMillan, 46-66.

Bennett, P., 2006. *Organic gardening*, Sydney, New Holland Publishers.

Bettini, Y., Brown, R. R. & de Haan, F. J., 2015. Exploring institutional adaptive capacity in practice: examining water governance adaptation in Australia. *Ecology and Society*, 20, no. 1, 47-66.

Breuste, J. H., 2004. Decision making, planning and design for the conservation of indigenous vegetation within urban development. *Landscape and urban Planning*, 68, no. 4: 439-452

Brown, R., Keath, N. & Wong, T., 2009. Urban water management in cities: historical, current and future regimes. *Water Science and Technology*, 59, no. 5, 847-855.

Bureau of Meteorology (BoM), 2015. National Performance Report 2013–2014: Urban Water Utilities, Part A, BoM, Melbourne, viewed 4 December 2016, http://www.bom.gov.au/water/npr/docs/2014-15/National-performance-report-2014-15_part-A_lowres.pdf.

Burns, M., Ladson, A. & Fletcher, T., 2015. Impact of rainwater tanks of urban hydrology and stormwater quality. In Ashok Sharma, Donald Begbie & Ted Gardner (eds), *Rainwater Tank Systems for Urban Water Supply*, London, IWA Publishing.

Byrne, J., 2007. *The Green Gardener*, VIC, Penguin.

Byrne, J., 2013. *Small Space Organics*, VIC, Hardie Grant Books.

Byrne, J., Hunt, J., Anda, M. & Ho, G. Meeting plant water demands with greywater. *Proceedings of the AWA Onsite and Decentralised Sewerage Conference*, 12–15 October 2008, VIC.

Byrne, J., Sturman, J., Anda, M., Mathew, K. & Ho, G., Water conservation in urban landscaping using a low-cost soil moisture controller. *Proceedings of the Water and Wastewater: Perspectives of Developing Countries (WAPDEC) Conference*, 11–13 December 2002, New Delhi.

Calvet-Mir, L., Gómez-Baggethun, E. & Reyes-Garcia, V., 2012. Beyond food production: Ecosystem services provided by home gardens. A case study in Vall Fosca, Catalan Pyrenees, North eastern Spain. *Ecological Economies*, 74, 153-160.

Cameron, R., Blanusa, T., Taylor, J., Salisbury, A., Halstead, A., Henricot, B. & Thompson, K., 2012. The domestic garden – Its contribution to urban green infrastructure. *Urban Forestry and Urban Greening*, 11, 129-137.

Cape, J., 2006. Urban Irrigation Best Management Practice Guidelines. Irrigation Association of Australia, NSW.

Chow, J., Kopp, R. J. & Portney, P. R., 2003. Energy resources and global development. *Science*, 302, no. 5650, 1528-1531.

Chong, M., Umapathi, S., Mankad, A., Gardner, E.A., Sharma, A. and Biermann, S., 2011. Estimating water savings from mandated rainwater tanks in South East Queensland. *Urban Water Security Research Alliance, Brisbane*.

Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology, 2015. Climate change in Australia: Projections for Australia's NRM Regions, Australia, viewed 4 December 2016, https://publications.csiro.au/rpr/download?pid=csiro:EP154327&dsid=DS2.

Connellan, G., 2013. *Water Use Efficiency for Irrigated Turf and Landscape*, VIC, CSIRO Publishing.

Coombes, P. & Barry, M. 2007. Efficiency of roof and traditional water supply catchment subject to climate change. *Proceedings of the RW and Urban Design 2007 Conference*, Sydney 2007, 177-184.

Coombes, P., & Kuczera, G. 2001. RW tank design for water supply and stormwater management. *Proceedings of the Stormwater Association 2001 Regional Conference*, 2001, NSW.

Coombes, P. & Kuczera, G. 2003. Analysis of the Performance of RW Tanks in Australian Capital Cities. *Proceedings of the 28th International Hydrology and Water Resources Symposium*, 10–14 November 2003, NSW.

Coombes, P.J., Kuczera, G. and Kalma, J.D., 2003. Economic, water quantity and quality impacts from the use of a rainwater tank in the inner city. *Australian Journal of Water Resources*, 7(2), 111-120.

Costello, L., Matheny, N. & Clark, J., 2000. A Guide to Estimating Irrigation Water Needs of Landscape Plantings in California: The Landscape Coefficient Method and WUCOLS III, University of California Cooperative Extension and California Department of Water Resources, CA.

Crawford, D., 2015. *Garden Pests, Diseases and Good Bugs*, Sydney, Harper Collins Publishers, Australia Pty Ltd.

Crites, R. & Technobanoglous, G., 1998. *Small and decentralized wastewater management systems*. McGraw-Hill.

Cross, R. & Spencer, R., 2008. *Sustainable Gardens*, VIC, CSIRO Publishing.

Daigger, G. T., 2009. Evolving urban water and residuals management paradigms: Water reclamation and reuse, decentralization, and resource recovery. *Water Environment Research*, 81, no. 8, 809-823.

Daigger, G. T. & Crawford, G. V., 2007. Enhancing water system security and sustainability by incorporating centralized and decentralized water reclamation and reuse into urban water management systems. *Journal of Environmental Engineering and Management*, 17, no. 1, 1-10.

Dallas, S., Anda, M. & Ho, G. Towards a zero emissions development approach to water and nutrients in urban villages. *Proceedings of the Society for Sustainability and Environmental Engineering (SSEE) Conference*, 31 October – 2 November 2007, Perth.

Davis, S. & Dukes, M., 2010. Irrigation. *Irrigation scheduling performance by evapotranspiration-based controllers*, 98, no. 1, 19-28.

Deelstra, T., & Girardet, H., 2000. *Urban Agriculture and Sustainable Cities: Thematic Paper 2*, National Science Foundation (NSF), Virginia.

Department of Health (DoH). 2005. Code of Practice for the Reuse of GW in Western Australia, Government of Western Australia, DoH, Perth.

Department of Health (DoH). 2010. Code of Practice for the Reuse of GW in Western Australia, Government of Western Australia, DoH, Perth, viewed 4 December 2016, http://ww2.health.wa.gov.au/~/media/Files/Corporate/general%20documents/water/PDF/Code%20of%20practice%20for%20the%20reuse%20of%20greywater%20in%20WA%20010_v2_130103.ashx.

Department of Water (DoW). 2009. Perth Regional Aquifer Modelling System (PRAMS) model development: Application of the Vertical Flux Model, Hydrological Record Series, Report No. HG27, Government of Western Australia, DoW, Perth, viewed 4 December 2016, https://www.water.wa.gov.au/__data/assets/pdf_file/0004/4459/84333.pdf.

Department of Water (DoW). 2011. Operational policy 5.17: Metropolitan domestic garden bores, Government of Western Australia, DoW, Perth, viewed 4 December 2016, https://www.water.wa.gov.au/__data/assets/pdf_file/0014/1706/99735.pdf.

Department of Water (DoW). 2014. Water for Growth, Government of Western Australia: Perth, viewed 4 December 2016, http://www.water.wa.gov.au/__data/assets/pdf_file/0013/2614/107261.pdf.

Department of Water (DoW). 2015. Winter Sprinkler Ban, viewed 4 December 2016, http://www.water.wa.gov.au/urban-water/water-restrictions/garden-bores/winter-sprinkler-ban.

Dewaelheyns, V., Rogge, E. & Gulinck, H., 2014. Putting domestic gardens on the agenda using empirical spatial data: The case of Flanders. *Applied Geography*, 50, 132-143.

Dhakal, R. S., Syme, G., Andre, E. & Sabato, C., 2015. Sustainable water management for urban agriculture, gardens and public open space irrigation: A case study in Perth. *Agricultural Sciences*, 6, no. 7, 676-685.

Diaper, C., 2004. *Innovation in on-site domestic water management systems in Australia: A review of rainwater, greywater, stormwater and wastewater utilisation techniques*, VIC, CSIRO, Australian Water Conservation and Reuse Research Program.

Diaper, C., Tjandraatmadja, G. & Kenway, S.J., 2007. *Sustainable subdivisions: Review of technologies for integrated water services*. CRC for Construction Innovation.

Dillon, P., Page, D., Dandy, G., Leonard, R., Tjandraatmadja, G., Vanderzalm, J., Rouse, K., Barry, K., Gonzalez, D. & Myers, B., 2014. Managed aquifer recharge and stormwater use options: Summary of research findings. *Goyder Institute for Water Research, Technical Report*, 14, 13, viewed 4 December 2016, http://www.goyderinstitute.org/uploads/MARSUO-Summary%20of%20Research%20Findings-final_web.pdf.

Domènech, L. & Sauri, D., 2010. Socio-technical transitions in water scarcity contexts: Public acceptance of greywater reuse technologies in the Metropolitan Area of Barcelona. *Resources, Conservation and Recycling*, 55, no. 1, 53-62.

e Silva, M.D.F.M., Calijuri, M.L., de Sales, F.J.F., de Souza, M.H.B. & Lopes, L.S., 2014. Integration of technologies and alternative sources of water and energy to promote the sustainability of urban landscapes. *Resources, Conservation and Recycling*, 91, 71-81.

Australian Energy Regulator. 2016. Energy Made Easy - Australian Government, viewed 4 December 2016, http://www.energymadeeasy.gov.au

Evans, C., Anda, M., Dallas, S. & Ho, G. E. Demonstration of decentralised wastewater recycling in urban villages in Western Australia. *Proceedings of the Singapore International Water Week Conference*, 1–5 July 2012, Singapore.

Evans, C., Radin-Mohamed, R., Anda, M., Dallas, S., Mathew, K., Jamieson, S. & Milani, S. Greywater recycling in Western Australia: policy, practice and technologies. *Proceedings of the Onsite and Decentralised Sewerage and Recycling Conference*, 12–15 October 2008, VIC.

Evans, C. S., Anda, M. & Dallas, S., 2009. An assessment of mains water savings achieved through greywater reuse at a household scale in Perth, Western Australia. *Proceedings of the 6th International Water Sensitive Urban Design Conference and Hydropolis no. 3*, Perth, 464-471.

Fanton, M. & Fanton, J., 1993. *The Seed Savers Handbook*, NSW, The Seed Savers Network.

Ferguson, M., 2011. Rainwater tank monitoring report: A 12-month one-minute interval data study of RW tank water savings and energy use for 52 real life installations, Sydney Water, Sydney, viewed 4 December 2016, https://www.sydneywater.com.au/web/groups/publicwebcontent/documents/document/zgrf/mdu2/~edisp/dd_056073.pdf.

Freeman, C., Dickinson, K. J. M., Porter, S. & van Heezik, Y., 2012. “My garden is an expression of me”: Exploring householders’ relationships with their gardens. *Journal of Environmental Psychology*, 32, no. 2, 135-143.

French, J., 1997. *Organic Control of Common Weeds: A Safe Environment Guide*, Melbourne, Arid Books.

French, J., 2002. *Natural Control of Garden Pests*, vol. 2, Melbourne, Arid Books.

Friedler, E. & Hadari, M., 2006. Economic feasibility of on-site greywater reuse in multi-storey buildings. *Desalination*, 190, no. 1, 221-234.

Friedler, E., Hadari, M. & Penn, R., 2012. Evaluation of the effects of greywater reuse on domestic wastewater quality and quantity. *Urban Water Journal*, 9, no. 3, 137-148.

Galluzzi, G., Eyzaguirre, P. & Negri, V., 2010. Home gardens: neglected hotspots of agro-biodiversity and cultural diversity. *Biodiversity and Conservation*, 19, no. 13, 3635-3654.

Garnett, T., 1996. Growing Food in Cities: A Report to Highlight and Promote the Benefits of Urban Agriculture in the UK, National Food Alliance (NFA), London.

Gaston, K., Thompson, K., Warren, P. & Smith, R., 2005. Urban domestic gardens (IV): the extent of the resource and its associated features. *Biodiversity and Conservation*, 14, no. 14, 3327-3349.

Gaston, K. J., Thompson, K., Warren, P. H. & Smith, R. M., 2005. Urban domestic gardens (IV): the extent of the resource and its associated features. *Biodiversity and Conservation*, 14, 3327-3349.

Gaston, K. J., Fuller, R. A., Loram, A., MacDonald, C., Power, S. & Dempsey, N., 2007. Urban domestic gardens (XI): variation in urban wildlife gardening in the United Kingdom. *Biodiversity and Conservation*, 16, 3227-3238.

Ghaitidak, D. M. & Yadav, K. D., 2013. Characteristics and treatment of GW – a review. *Environmental Science and Pollution Research*, 20, no. 5, 2795-2809.

Ghisi, E. & de Oliveria, S. M., 2007. Potential for portable water savings by combining the use of rainwater and greywater in houses in southern Brazil. *Building and Environment*, 42, no. 4, 1731-1742.

Ghisi, E. & Ferreira, D. F., 2007. Potential for portable water savings by using rainwater and greywater in a multi-storey residential building in southern Brazil. *Building and Environment*, 42, no. 7, 2512-2522.

Ghunmi, L. A., Zeeman, G., Fayyad, M., & van Lier, J. B., 2011. Grey water treatment systems: a review. *Critical Reviews in Environmental Science and Technology*, 41, no. 7, 657-698.

Glowinski, L., 1997. *The Complete Book of Fruit Growing in Australia: over 200 temperate and subtropical fruits, nuts and berries to grow in gardens, farms or orchards*, Sydney, Hachette Australia Pty Ltd.

Gardner, E.A., 2003. Some examples of water recycling in Australian urban environments: a step towards environmental sustainability. *Water Science and Technology: Water Supply*, 3, no. 4, 21-31.

Goddard, M., Dougill, A. & Benton, T., 2013. Why garden for wildlife? Social and ecological drivers, motivations and barriers for biodiversity management in residential landscapes. *Ecological Economics*, 86, 258-273.

Gosh, S., 2010. Sustainability potential of suburban gardens: review and new directions. *Australian Journal of Environmental Management*, 17, no. 3, 156-175.

Grant, P., 2003. *Habitat Garden: Attracting Wildlife to your Garden*, ABC Books, Sydney.

Gray, S. R. 2002. Reducing portable water use – a comparison of on-site GW treatment systems and rain tanks in urban environments. *Proceedings of the Sustainability of Water Resources – International Conference*, 13–14 November 2002, Perth.

Grose, M. J., 2009. Changing relationships in public open space and private open space in suburbs in south-western Australia. *Landscape and Urban Planning*, 92, no.1, 53-63.

Gross, A., Azulai, N., Oron, G., Ronen, Z., Arnold, M. & Nejidat, A., 2005. Environmental impact and health risks associated with greywater irrigation: a case study. *Water Science & Technology*, 52, no. 8, 161-169.

Gross, A., Shmueli, O., Ronen, Z. & Raveh, E., 2006. Recycled vertical flow constructed wetland (RVFCW) – a novel method of recycling greywater for irrigation in small communities and households. *Chemosphere*, 66, no. 5, 916-923.

Gross, A. Kaplan, D. & Baker, K., 2007. Removal of chemical and microbiological contaminants from domestic greywater using a recycled vertical flow bioreactor (RVFB). *Ecological Engineering*, 31, no. 2, 107-114.

Gross, A., Wiel-Shafran, A., Bondarenko, N. & Ronen, Z., 2008. Reliability of small scale GW treatment systems and the impact of its effluent on soil properties. *International Journal of Environmental Studies*, 65, no. 1, 41-50.

Gross, A., Maimon, A., Alfiya, Y. & Friedler, E., 2015. *Greywater Reuse*, FL, CRC Press.

Gross, H. and Lane, N., 2007. Landscapes of the lifespan: Exploring accounts of own gardens and gardening. *Journal of Environmental Psychology*, 27, no.3, 225-241.

Grübler, A. & Nakićenović, N., 1996. Decarbonizing the global energy system. *Technological Forecasting and Social Change*, 53, no. 1, 97-110

Gurung, T.R., Umapathi, S. and Sharma, A.K., 2012. *Economics of Scale Analysis of Communal Rainwater Tanks*. Urban Water Security Research Alliance, viewed 4 December 2016, https://publications.csiro.au/rpr/download?pid=csiro:EP126329&dsid=DS2.

Gurung, T. R. & Sharma, A., 2014. Communal rainwater tank systems design and economies of scale. *Journal of Cleaner Production*, 67, 26-36.

Hall, T., 2010. *The Life and Death of the Australian Backyard*, VIC, CSIRO Publishing.

Handreck, K. & Black, N., 2010. *Growing media for ornamental plants and turf* (ed. 4), NSW, UNSW Press.

Harremoës, P., 1997. Integrated water and waste management. *Water Science and Technology*, 35, no. 9, 11-20.

Harrington, N. & Cook, P., 2014. *Groundwater in Australia*, Flinders University, National Centre for Groundwater Research and Training, Adelaide, viewed 4 December 2016, http://www.groundwater.com.au/media/W1siZiIsIjIwMTQvMDMvMjUvMDFfNTFfMTNfMTMzX0dyb3VuZHdhdGVyX2luX0F1c3RyYWxpYV9GSU5BTF9mb3Jfd2ViLnBkZiJdXQ/Groundwater%20in%20Australia_FINAL%20for%20web.pdf.

Hauber-Davidson, G. & Shortt, J., 2011. Energy consumption of domestic rainwater tanks: why supplying rainwater uses more energy than it should. *Water: Journal of the Australian Water Association*, 38, no. 3, 72.

Head, L. & Muir, P. 2007. *Backyard: Nature and culture in Suburban Australia*, NSW, University of Wollongong Press.

Ho, G., Dallas, S., Anda, M. & Mathew, K., 2001. On-site wastewater technologies in Australia. *Water Science and Technology*, 44, no. 6, 81-88.

Ho, G. & Anda, M., 2006. Centralised versus decentralised wastewater systems in an urban context: the sustainability dimension. In *2nd IWA Leading Edge on Sustainability in Water Limited Environments*, Sydney, IWA Publishing, 81-89.

Ho, G., Anda, M. & Hunt, J., 2008. Rainwater harvesting at urban land development scale: Mimicking nature to achieve sustainability. *Proceedings of IWA World Water Congress*, 7–12 September 2008, Vienna.

Hollo, N., 2005. *Warm House Cool House*, NSW, UNSW Press.

Hughes, R., Dallas, S. & Anda, M. Nutrient management, wastewater recycling and urine separation: A potential method for effective nutrient and irrigation practices in Western Australia. *Proceedings of International Conference on Decentralised Water and Wastewater Systems*, 10–12 July 2006, Fremantle.

Hunt, J., Anda, M., Mathew, K., Ho, G. & Priest, G., 2005. Emerging approaches to integrated urban water management: Cluster scale application. *Water Science and Technology*, 51, no. 10, 21-27.

Hunt, J., Anda, M., Dallas, S. & Ho, G. 2011a. Rainwater harvesting systems for local government buildings, three case studies. *Proceedings of International Conference on Integrated Water Management*, 2–5 February 2011, Perth.

Hunt, J., Anda, M. & Ho, G., 2011b. Water balance modelling of alternate water sources at the household scale. *Water Science and Technology*, 63, no. 9, 1873-79.

Irrigation Association (IA) & American Society of Irrigation Consultants (ASIC) 2014. Landscape Irrigation Best Management Practices, IA/ASIC, VA/MI, viewed 4 December 2016, https://www.irrigation.org/uploadedFiles/Standards/BMPDesign-Install-Manage.3-18-14(2).pdf.

Irrigation Australia (IA) 2012. Standards for Domestic Irrigation Installation, IA (WA Region), Perth.

Jansson, A., 2012. Reaching for a sustainable, resilient urban future using the lens of ecosystem services. *Ecological Economics*, 86, 285-91.

Johnson, P., 2014. *Connected: The Sustainable Landscapes of Phillip Johnson*, Murdoch Books.

Josh Byrne and Associates (JBA), 2013. Residential Grey-water Plumbing Guidelines, JBA, Fremantle, viewed 4 December 2016, http://www.gwig.org/downloads/files/130613%20Residential%20Greywater-Ready%20Plumbing%20Guidelines%20Final.pdf.

Keller, J. & Bliesner, R., 2014. *Sprinkle and Trickle Irrigation*. Springer, New York.

Keisling, F. & Manning, C., 2010. How green is your thumb? Environmental gardening identity and ecological gardening practices. *Journal of Environmental Psychology*, 30, 315-27.

Keoleian, G. A., Blanchard, S. & Reppe, P., 2000. Life-cycle energy, costs, and strategies for improving a single-family house. *Journal of Industrial Ecology*, 4, no. 2, 135-56.

Khan, S., Mushtaq, S., Hanjra, M.A. & Schaeffer, J., 2008. Estimating potential costs and gains from an aquifer storage and recovery program in Australia. *Agricultural Water Management*, 95, no. 4, 477-488.

Khan, S., Khan, M. A., Hanjra, M. A. & Mu, J., 2009. Pathways to reduce the environmental footprints of water and energy inputs in food production. *Food policy* 34, no. 2, 141-49.

Kim, Ke Chun, 1993. Biodiversity, conservation and inventory: why insects matter. *Biodiversity & Conservation*, 2, no. 3, 191-214.

Kortright, R. & Wakefield, S., 2010. Edible backyards: a qualitative study of household food growing and its contributions to food security. *Agriculture and Human Values*, 28, no. 1, 39-53.

Kunz, N.C., Fischer, M., Ingold, K. & Hering, J.G., 2016. Drivers for and against municipal wastewater recycling: a review. *Water Science and Technology*, 73, no. 2, 251-259.

Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. *Science*, 304, no. 5677, 1623-27.

Larsen, T. A., 2011. Redesigning wastewater infrastructure to improve resource efficiency. *Water Science and Technology*, 63, no. 11, 2535-41.

Li, F., Wichmann, K. & Otterpohl, R., 2009. Review of the technological approaches for grey water treatment and reuses. *Science of the total Environment*, 407, no. 11, 3439-49.

Lieb, D., Brennan, D. & McFarlane, D., 2006. *The economic value of groundwater used to irrigate lawns and gardens in the Perth metropolitan area*. Technical report. CSIRO: Water for a Healthy Country National Research Flagship, Canberra, viewed 4 December 2016, https://publications.csiro.au/rpr/download?pid=procite:32b8e0e6-a8c4-4762-9bc1-baf8045a43ae&dsid=DS1.

Loram, A., Tratalos, J., Warren, P. H. & Gaston K. J., 2007. Urban domestic gardens (X): the extent and structure of the resource in five major cities. *Landscape Ecology*, 22, 601-615.

Loram, A., Warren, P. & Gaston, K., 2008. Urban domestic gardens (XIV): the characteristics of gardens in five cities. *Environmental Management*, 42, 361-376.

Loram, A., Warren, P., Thompson, K. & Gaston, K., 2011. Urban domestic gardens: the effects of human interventions on garden composition. *Environmental Management*, 48, 808-824.

Loux, J., Winter-Skonovd, R. & Gellerman, E., 2012. Evaluation of combined rainwater and greywater systems for multiple development types in Mediterranean climates. *Journal of Water Sustainability*, 2, no. 1, 55-77.

Ma, X., Xue, X., Gonzalez-Mejia, A., Garland, J. & Cashdollar, J., 2015. Sustainable water systems for the city of tomorrow: a conceptual framework. *Sustainability*, 7, no. 9, 12071-105.

Maheshwari, B. L., & Pinto, U., 2015. Sustainable greywater reuse for residential landscape irrigation a critical review. *Chinese Journal of Population Resources and Environment*, 13, no. 3, 250-264.

Maimon, A., Friedler, E. & Gross, A., 2014. Parameters affecting greywater quality and its safety for reuse. *Science of the Total Environment*, 487, 20-25.

Margni, M., Rossier, D., Crettaz, P. & Jolliet, O., 2002. Life cycle impact assessment of pesticides on human health and ecosystems. *Agriculture, Ecosystems & Environment*, 93, no. 1, 379-392.

Marlow, D.R., Moglia, M., Cook, S. and Beale, D.J. 2013. Towards sustainable urban water management: A critical reassessment. W*ater Research*, 47, no. 20, 7150-7161.

Marsalek, D., Rochfort, M. & Savic, P., 2001. Urban water as a part of integrated catchment management. In C. Maksimovic & J. Tejada-Guilbert (eds.) *Frontiers in Urban Water Management Deadlock Hope*, IWA Publishing, London, 37-83.

Marsden Jacob Associates (MJA), 2009. Waterwise rebate program review. Report prepared for the Water Corporation, MJA, Perth.

Marsden Jacob Associates (MJA), 2011. The economic impact of emergency outdoor water use restrictions in Perth. Report prepared for the Water Corporation and the Department of Water, MJA, Perth.

Marshall, T., 2003. *Recycle Your Garden: The Essential Guide to Composting*, Sydney, ABC Books.

Mathew, K., Anda, M. & Ho, G. Integrated urban water management, Principles for urban developments. *Proceedings of Water and Wastewater Management for Developing Countries Conference*, 28–30 July 2005, Zimbabwe.

Mathieu, R., Freeman, C. & Aryal, J., 2007. Mapping private gardens in urban areas using object-oriented techniques and very high-resolution satellite imagery. *Landscape and Urban Planning*, 81, no. 3, 179-192.

Matthies, P. & Marty, T., 2013. Does ecological gardening increase species richness and aesthetic quality of a garden? *Biological Conservation*, 159, 37-44.

McArthur, W. M. 2004. Reference soils of south-western Australia; Australian Society of Soil Science W.A. Branch and Department of Agriculture and Food, viewed 4 December 2016, http://researchlibrary.agric.wa.gov.au/books/4.

McFarlane, D.J., Smith, A., Bekele, E., Simpson, J. & Tapsuwan, S., 2009. Using treated wastewater to save wetlands impacted by climate change and pumping. *Water Science and Technology*, 59, no. 2, 213-221.

McFarlane, D., Stone, R., Martens, S., Thomas, J., Silberstein, R., Ali, R. & Hodgson, G., 2012. Climate change impacts on water yields and demands in south-western Australia. *Journal of Hydrology*, 475, 488-498.

McFarlane D.J (ed.), 2015. Recycled water for heavy industry and preventing sea water intrusion. A report to the Australian Water Recycling Centre of Excellence Government and industry partners from the CSIRO Land and Water Flagship, viewed 4 December 2016, https://publications.csiro.au/rpr/download?pid=csiro:EP155284&dsid=DS2.

McMaugh, J., 2000. *What Garden Pest or Disease is That? Organic and Chemical Solutions for Every Garden Problem*, Sydney, New Holland Publishers.

McKinney, M. L., 2002. Urbanization, biodiversity, and conservation. *BioScience*, 52, no. 10, 883-890.

Memon, F.A., Butler, D., Han, W., Liu, S., Makropoulos, C., Avery, L.M. & Pidou, M., 2005. Economic assessment tool for greywater recycling systems. *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, 158, no. 3, 155-161. ICE Publishing.

Memon, F. A. & Ward, S., 2015. *Alternative water supply systems*, London, IWA Publishing.

Mendel, J., 2012. *Urban Sanctuary: Designing Small Gardens*, Victoria, Hardie Grant Books.

Metcalf & Eddy, Inc. 1991. *Wastewater Engineering: Treatment, Disposal, and Reuse* (3rd ed.), McGraw-Hill, New York.

Mitchell, G., Mein, R. G. & McMahon, T. A., 2001. Modelling the urban water cycle. *Environmental Modelling and Software*, 16, no. 7, 615-629.

Mitchell, G., 2004. Integrated urban water management. *A Review of Current Australian Practice.* Australian Water Association and CSIRO, Melbourne, Victoria.

Mohamed, R. M. S. R., Kassim, A. H. M., Anda, M. & Dallas, S., 2013. A monitoring of environmental effects from household greywater reuse for garden irrigation. *Environmental Monitoring and Assessment*, 185, no. 10, 8473-88.

Mollison, B., 1988. *Permaculture: A Designers Manual*, NSW, Tagari Publications.

Mourad, K. A., Berndtsson, J. C. & Berndtsson, R., 2011. Potential fresh water saving using greywater in toilet flushing in Syria. *Journal of Environmental Management*, 92, no. 10, 2447-53.

National Water Commission (NWC), 2008a. Rainwater Tank Design and Installation Handbook, Australian Government, NWC, Raising National Water Standards Program, Canberra.

National Water Commission (NWC), 2008b. Urban Greywater Design and Installation Handbook, Australian Government, NWC, Raising National Water Standards Program, Canberra.

Newman, P. 1999. Sustainability and cities: extending the metabolism model. *Landscape and urban planning*, 44, no.4, 219-226.

Newman, P. 2006. The environmental impact of cities. *Environment and Urbanization*, 18, no. 2, 275-295.

Newman, P., Beatley, T. & Boyer, H., 2009. *Resilient Cities: Responding to Climate Change and Peak Oil*, Washington DC, Island Press.

Newman, P. & Jennings, I., 2008. *Cities as Sustainable Ecosystems: Principles and Practices*, Washington DC, Island Press.

Newman, P. & Matan, A., 2013. *Green urbanism in Asia*, Singapore, World Scientific Publications.

Newman, P. W. G., 1993. Prioritising urban water research. *Proceedings of the 15th Australian Water and Wastewater Association Federal Convention, Urban Water Research Forum*, 18–23 April 1993, Gold Coast.

Newman, P. W. G. & Kenworthy, J. R., 1999. *Sustainability and Cities*, Washington DC, Island Press.

Ng, M., 2004. Household Greywater Reuse for Garden Irrigation in Perth, University of Western Australia, Centre for Water Research, Perth, viewed 4 December 2016, http://www.web.uwa.edu.au/__data/assets/pdf_file/0003/1637310/Ng_MayLe_2004.pdf/.

Nodle, E., 2000. Greywater reuse systems for toilet flushing in multi-storey buildings – over ten years' experience in Berlin. *Urban Water*, 1, no. 4, 275-84.

Nolan, M., Rikard-Bell, G., Mohsin, M. & Williams, M., 2006. Food insecurity in three socially disadvantaged localities in Sydney, Australia. *Health Promotion Journal of Australia* 17, no. 3, 247.

Page, D., Gonzalez, D., Sidhu, J., Toze, S., Torkzaban, S. & Dillon, P., 2015. Assessment of treatment options of recycling urban stormwater recycling via aquifers to produce drinking water quality. U*rban Water Journal* 13 (6): 657-62.

Paker, Y., Yom-Tov, Y., Alon-Mozes, T. & Barnea, A., 2014. The effect of plant richness and urban garden structure on bird species richness, diversity and community structure. *Landscape and Urban Planning*, 122, 186-195.

Patterson, R. A. Water efficiency, domestic appliances and hydraulic design for on-site systems. *Proceedings of the 1st International Conference on Onsite Wastewater Treatment and Recycling*, 11–13 February 2004, Perth.

Penn, R., Friedler, E. & Ostfeld, A., 2013. Multi-objective evolutionary optimization for greywater reuse in municipal sewer systems. *Water Research,* 47, no. 15, 5911-5920.

Pidou, M., Memon, F.A., Stephenson, T., Jefferson, B. & Jeffrey, P., 2007, September. Greywater recycling treatment options and applications. *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, 160, no. 3, 119-131. ICE Publishing.

Priest, G., Anda, M., Mathew, K. & Ho, G. Domestic greywater reuse as part of a total urban water management strategy. *Proceedings of the International Sustainability of Water Resources Conference*, 13–14 November 2004, Perth.

Prince, G., 1997. Urban water balance model: user's guide. Internal report, Government of Western Australia, Water and River Commission, Perth.

Raucher, R.S. & Tchobanoglous, G., 2014. *The opportunities and economics of direct potable reuse*. Alexandria VA: Water Reuse Research Foundation, viewed 4 December 2016, https://watereuse.org/wp-content/uploads/2015/05/OppsEconDPR-webcast.pdf.

Radcliffe, J.C., 2006. Future directions for water recycling in Australia. *Desalination*, 187, no. 1, 77-87.

Reading, D., 1990. *A guide to keeping poultry in Australia*, VIC, Viking.

Rees, W.E., 1992. Ecological footprints and appropriated carrying capacity: what urban economics leaves out. *Environment and urbanization*, 4, no. 2, 121-130.

Reeves, D. W., 1997. The role of soil organic matter in maintaining soil quality in continuous cropping systems. *Soil and Tillage Research* 43, no. 1, 131-167.

Retamal, M., Turner, A. & Whilte, S., 2009. Energy Implications of household rainwater systems. *Water Journal,* 36, no. 8, 70-75.

Revell, G. & Anda, M., 2014. Sustainable urban biophilia: the case of greenskins for urban density. *Sustainability*, 6, no. 8, 5423-5438.

Romero, R., Muriel, J.L., García, I. & de la Pena, D.M., 2012. Research on automatic irrigation control: State of the art and recent results. *Agricultural water management*, 114, 59-66.

Ryan, A. M., Spash, C. L. & Measham, T. G., 2009. Socio-economic and psychological predictors of domestic greywater and rainwater collection: Evidence from Australia. *Journal of Hydrology*, 379, no. 1-2, 164-171.

Sharma, A., Burn, S., Gardner, T. and Gregory, A., 2010. Role of decentralised systems in the transition of urban water systems. *Water Science and Technology: Water Supply*, 10, no. 4, 577-583.

Sharma, A.K., Tjandraatmadja, G., Cook, S. and Gardner, T., 2013. Decentralised systems–definition and drivers in the current context. *Water Science and Technology*, 67, no. 9, 2091-2101.

Sharma, A.K., Begbie, D. & Gardner, T., 2015. *Rainwater tank systems for urban water supply: Design, yield, energy, health risks, economics and social perceptions*. IWA Publishing.

Sharma, A.K., Pezzaniti, D., Myers, B., Cook, S., Tjandraatmadja, G., Chacko, P., Chavoshi, S., Kemp, D., Leonard, R., Koth, B. & Walton, A., 2016. Water sensitive urban design: An investigation of current systems, implementation drivers, community perceptions and potential to supplement urban water services. *Water*, 8, no. 7, 272.

Shrewsbury, P. M. & Leather, S. R., 2012. Using biodiversity for pest suppression in urban landscapes. In *Biodiversity and Insect Pests: Key Issues for Sustainable Management*, Chichester, Wiley-Blackwell, 293-308.

Sitzenfrei, R., Moderl, M. & Rauch, W., 2013. Assessing the impact of transitions from centralised to decentralised water solutions on existing infrastructures: Integrated city-scale analysis with VIBe. *Water Research*, 47, no. 20, 7251-7263.

Smith, A., Pollock, D. & McFarlane, D., 2005. Opportunity for additional self-supply of groundwater from the superficial aquifer beneath metropolitan Perth. Client report, viewed 4 December 2016, https://publications.csiro.au/rpr/download?pid=procite:7311f9d1-aa1a-4c15-87d4-bf05065ad0ce&dsid=DS1.

Sofoulis, Z., 2005. Big Water, everyday water: a sociotechnical perspective. Continuum: Journal of Media & Cultural Studies, 19, no. 4, December 2005, 445-463.

St Hilaire, R., Arnold, M. A., Wilkerson, D. C., Devitt D. A., Hurd, B. H., Lesikar, B. J., & Lohr, V. I., 2008. Efficient water use in residential urban landscapes. *HortScience* 43, no. 7, 2081-2092.

Standards Australia (SA), 2003. AS/NZS 3500 Plumbing and Drainage – Part 1 Water Services, SA, Sydney.

Standards Australia (SA), 2005. ATS 5200:460 Technical Specification for Plumbing and Drainage Products – GW Diversion Device, SA, Sydney.

Standards Australia (SA), 2008. HB 326 – 2008, Urban GW Installation Handbook for Single Households, SA, Sydney.

Standards Australia (SA), 2012. AS/NZS 1547 On-site Domestic Wastewater Management, SA, Sydney.

Standards Australia (SA), 2013. ATS 5200 Technical Specification for plumbing and Drainage Products – Procedures for Certification of Plumbing and Drainage Products, SA, Sydney.

Sturman, J., Ho, G. & Mathew, K., 2004. *Water Auditing and Water Conservation*, Cornwall, IWA Publishing.

Swart, R., Robinson, J. & Cohen, S., 2003. Climate change and sustainable development: expanding the options. *Climate Policy*, 3, no. sup1: S19-S40.

Syme, G. J., Shao, Q., Po, M. & Campbell, E., 2004. Predicting and understanding home garden water use. *Landscape and Urban Planning*, 68, no. 1, 121-128.

Synergy, 2016. Synergy Home Plan (A1) tariff, viewed 4 December 2016, https://www.synergy.net.au/Your-home/Energy-plans/Home-Plan-A1.

Thayer, R. J. & Asler, J. R., 1984. Water conserving landscape design. In E. G. McPherson (ed.), *Energy Conserving Site Design*, Watkins and Son, UT, 185-215.

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R. & Polasky, S., 2002. Agricultural sustainability and intensive production practices. *Nature*, 418, no. 6898, 671-677.

Tjandraatmadja, G., Retamel, M., Umapathi, S., & Hauber-Davidson, G. 2015. Impact of rainwater tanks of urban hydrology and stormwater quality. In Ashok Sharma, Donald Begbie & Ted Gardner (eds), *Rainwater Tank Systems for Urban Water Supply*, London, IWA Publishing.

Toifl, M., Bulteau, G., Diaper, C. & O'Halloran, R., 2015. Greywater recycling: guidelines for safe adoption. In F. A. Memon & S. Ward (eds), *Alternative Water Supply Systems*, London, IWA Publishing, 217-240.

Travis, M., Wiel-Shafran, A., Weisbrod, N. & Gross, A., 2010. Greywater reuse for irrigation: Effect on soil properties. *Science of the Total Environment*, 408, no. 12, 2501-2508.

Umapathi, S., Chong, M.N. & Sharma, A., 2012. Investigation and monitoring of twenty homes to understand mains water savings from mandated rainwater tanks in South East Queensland. *Urban Water Security Research Alliance Technical Report*, 63, viewed 4 December 2016, https://publications.csiro.au/rpr/download?pid=csiro:EP124966&dsid=DS4.

Umapathi, S., Chong, M. & Sharma, A., 2013. Evaluation of plumbed rainwater tanks in households for sustainable water resource management: a real-time monitoring study. *Journal of Cleaner Production*, 42, 204-214.

Urban Development Institute of Australia (UDIA), 2015. The 2015 UDIA State of the Land Report, UDIA, National Land Supply Study (NLSP), Sydney.

Vieira, A. S., Beal, C. D., Ghisi, E. & Stewart, R., 2014. Energy intensity of rainwater harvesting systems: A review. *Renewable and Sustainable Energy Reviews*, 34, 225-242.

Vlachos, E. & Bragga, B., 2001. *The Challenge of Urban Water Management*, Cornwall, IWA Publishing.

Wallace, J. S., 2000. Increasing agricultural water use efficiency to meet future food production. *Agriculture, Ecosystems & Environment*, 82, no. 1, 105-119.

Water Corporation. 2009. Water forever: Towards climate resilience, WC, Perth, viewed 4 December 2016, https://www.watercorporation.com.au/-/media/files/about-us/planning-for-the-future/water-forever-50-year-plan.pdf.

Water Corporation. 2010. Perth residential water use study (PRWUS) 2008/2009: Final Report, WC, Perth, viewed 4 December 2016, https://www.water.wa.gov.au/__data/assets/pdf_file/0016/5272/98576.pdf

Water Corporation. 2013. Garden Bores, WC, Perth, viewed 4 December 2016, https://www.watercorporation.com.au/~/media/files/builders-and-developers/subdividing/garden-bores-fact-sheet.pdf.

Water Corporation. 2015. Annual Report, WC, Perth, viewed 4 December 2016, https://www.watercorporation.com.au/-/media/files/about-us/our-performance/annual-report-2015/water-corporation-annual-report-2015.pdf.

Water Corporation. 2016. Your bill and charges, viewed 4 December 2016, https://www.watercorporation.com.au/my-account/your-bill-and-charges.

Western Australian Water Resources Council (WAWRC) 1986. *Water Conservation through Good Design*, Perth, WAWRC.

Wilson, E. O., 1984. *Biophilia*. Harvard University Press.

Wiltshire, M., 2005. *Greywater Reuse in Urban Areas*, Brisbane, University of Southern Queensland.

Wong, T. & Brown, R., 2009. *Water Science and Technology*, 60, no. 3, 673-682.

Xing, Y., Hewitt, N. & Griffiths, P., 2011. Zero carbon buildings refurbishment: A hierarchical pathway. *Renewable and Sustainable Energy Reviews,* 15, no. 6, 3229-3236.

Zezza, A. & Tasciotti, L., 2010. Urban agriculture, poverty, and food security: Empirical evidence from a sample of developing countries. *Food policy*, 35, no. 4, 265-273.

APPENDICES

APPENDIX 1: ABC *GARDENING AUSTRALIA* STORIES AIRED ON NATIONAL TELEVISION: 2006–2016

CASE STUDY 1

Story Title	TX Date	Story Link
Creating a Small Garden	25/03/2006	http://www.abc.net.au/gardening/stories/s1599767.htm
Small Garden Introduction	25/03/2006	http://www.abc.net.au/gardening/stories/s1599767.htm
Raised Vegie Beds	6/05/2006	http://www.abc.net.au/gardening/stories/s1631789.htm
Greywater System	15/07/2006	http://www.abc.net.au/gardening/stories/s1686727.htm
Grafting and Planting Fruit Trees	12/08/2006	http://www.abc.net.au/gardening/stories/s1712911.htm
Rainwater Tanks	16/09/2006	http://www.abc.net.au/gardening/stories/s1741988.htm
Herbs and Perennials	30/09/2006	http://www.abc.net.au/gardening/stories/s1752163.htm
Recycling Organic Waste	11/11/2006	http://www.abc.net.au/gardening/stories/s1785437.htm
How to Make Compost	25/11/2006	http://www.abc.net.au/gardening/stories/s1796391.htm
Pest and Solutions	16/12/2006	http://www.abc.net.au/gardening/stories/s1805263.htm
Creating a Small Garden	17/03/2007	http://www.abc.net.au/gardening/stories/s1872506.htm
Creating a Small Garden – 2	14/04/2007	http://www.abc.net.au/gardening/stories/s1896277.htm
Small Garden Final	1/09/2007	http://www.abc.net.au/gardening/stories/s2021048.htm
Creating a Small Garden	5/01/2008	http://www.abc.net.au/gardening/stories/s2101784.htm
Edible Landscape	3/05/2008	http://www.abc.net.au/gardening/stories/s2233909.htm
Science of Watering	2/08/2008	http://www.abc.net.au/gardening/stories/s2321331.htm
Cage Potatoes	16/08/2008	http://www.abc.net.au/gardening/stories/s2336819.htm
Chewing Pests	30/08/2008	http://www.abc.net.au/gardening/stories/s2350386.htm
Maintaining Drip Irrigation	25/10/2008	http://www.abc.net.au/gardening/stories/s2400148.htm
Worm Castings	21/03/2009	http://www.abc.net.au/gardening/stories/s2522290.htm
Citrus Leaf Miner	28/03/2009	http://www.abc.net.au/gardening/stories/s2528879.htm
Dryland Garden	6/06/2009	http://www.abc.net.au/gardening/stories/s2589151.htm
Tool Maintenance	4/07/2009	http://www.abc.net.au/gardening/stories/s2613568.htm
Ceylon Spinach	22/08/2009	http://www.abc.net.au/gardening/stories/s2748869.htm
Rock Minerals	7/11/2009	http://www.abc.net.au/gardening/stories/s2730640.htm
Summer Preparation	28/11/2009	http://www.abc.net.au/gardening/stories/s2753459.htm
Slater Control	5/12/2009	http://www.abc.net.au/gardening/stories/s2748796.htm
Autumn Maintenance	27/03/2010	http://www.abc.net.au/gardening/stories/s2841842.htm
Greywater Tips	3/04/2010	http://www.abc.net.au/gardening/stories/s2861250.htm
Moving the Garden	15/05/2010	http://www.abc.net.au/gardening/stories/s2897703.htm

CASE STUDY 2

Story Title	TX Date	Story Link
Josh’s New Front Yard	29/05/2010	http://www.abc.net.au/gardening/stories/s2909627.htm
Vegie Garden Timber	12/06/2010	http://www.abc.net.au/gardening/stories/s2923542.htm
Josh’s New Back Yard	17/07/2010	http://www.abc.net.au/gardening/stories/s2954299.htm
Building a Veggie Bed	31/07/2010	http://www.abc.net.au/gardening/stories/s2966385.htm
Planting the Front Garden	28/08/2010	http://www.abc.net.au/gardening/stories/s2993176.htm
Potted Produce	18/09/2010	http://www.abc.net.au/gardening/stories/s3012324.htm
Ollies Garden	9/10/2010	http://www.abc.net.au/gardening/stories/s3031004.htm
Worm Farm Fridge	6/11/2010	http://www.abc.net.au/gardening/stories/s3056095.htm
Pruning an Olive Tree	20/11/2010	http://www.abc.net.au/gardening/stories/s3069071.htm
Building a Compost Bay	19/03/2011	http://www.abc.net.au/gardening/stories/s3165519.htm
Autumn Vegies	2/04/2011	http://www.abc.net.au/gardening/stories/s3177580.htm
Chasing the Sun – Bag Planting	30/04/2011	http://www.abc.net.au/gardening/stories/s3201841.htm
Front Garden Progress	4/06/2011	http://www.abc.net.au/gardening/stories/s3232882.htm
Simple Hydroponics	2/07/2011	http://www.abc.net.au/gardening/stories/s3256488.htm
Building a Bat Box	23/07/2011	http://www.abc.net.au/gardening/stories/s3274534.htm
Gabion Walls	30/07/2011	http://www.abc.net.au/gardening/stories/s3279167.htm
Josh’s Vegie Trials	6/08/2011	http://www.abc.net.au/gardening/stories/s3284748.htm
Early Spring Vegies	3/09/2011	http://www.abc.net.au/gardening/stories/s3306726.htm
Hot Box	3/09/2011	http://www.abc.net.au/gardening/stories/s3306806.htm
Spring Pruning	1/10/2011	http://www.abc.net.au/gardening/stories/s3326743.htm
Panting for Summer	5/11/2011	http://www.abc.net.au/gardening/stories/s3355369.htm
Irrigation Maintenance Tips	5/11/2011	http://www.abc.net.au/gardening/stories/s3354592.htm
Autumn Jobs	7/04/2012	http://www.abc.net.au/gardening/stories/s3471771.htm
Building for Bugs	23/06/2012	http://www.abc.net.au/gardening/stories/s3531551.htm
Growing Healthy	13/10/2012	http://www.abc.net.au/gardening/stories/s3606788.htm
Potted Success	27/04/2013	http://www.abc.net.au/gardening/stories/s3744201.htm
Working Worms	25/05/2013	http://www.abc.net.au/gardening/stories/s3763038.htm
Josh's Country	1/06/2013	http://www.abc.net.au/gardening/stories/s3770071.htm
Using Drip Irrigation	9/11/2013	http://www.abc.net.au/gardening/stories/s3885194.htm

CASE STUDY 3

Story Title	TX Date		Story Link
Josh's Dream	13/07/2013	Story	http://www.abc.net.au/gardening/stories/s3801322.htm
A Good Foundation	20/07/2013	Story	http://www.abc.net.au/gardening/stories/s3805887.htm
Edible Oasis	3/08/2013	Story	http://www.abc.net.au/gardening/stories/s3813326.htm
Planting for Privacy	10/08/2013	Story	http://www.abc.net.au/gardening/stories/s3821134.htm
Childs Play	24/08/2013	Story	http://www.abc.net.au/gardening/stories/s3832505.htm
A Succulent Garden	12/09/2013	Story	http://www.abc.net.au/gardening/stories/s3849599.htm
Productive Planting	28/09/2013	Story	http://www.abc.net.au/gardening/stories/s3857254.htm
Planting Companions	12/10/2013	Story	http://www.abc.net.au/gardening/stories/s3866987.htm
Time to Relax	23/11/2013	Story	http://www.abc.net.au/gardening/stories/s3893176.htm
Fruits of His Labour	5/04/2014	Story	http://www.abc.net.au/gardening/stories/s3978379.htm
Autumn Jobs	3/05/2014	Story	http://www.abc.net.au/gardening/stories/s3996390.htm
Perpetual Parsley	17/05/2014	Story	http://www.abc.net.au/gardening/stories/s4005917.htm
Hungry Citrus	24/05/2014	Story	http://www.abc.net.au/gardening/stories/s4010603.htm
Planting Winter Vegetables	31/05/2014	Story	http://www.abc.net.au/gardening/stories/s4016132.htm
Prune and Propagate	7/06/2014	Story	http://www.abc.net.au/gardening/stories/s4020227.htm
Filling the Gaps	28/06/2014	Story	http://www.abc.net.au/gardening/stories/s4034487.htm
Feeding the Soil	2/08/2014	Story	http://www.abc.net.au/gardening/stories/s4058634.htm
The Good Oil	9/08/2014	Story	http://www.abc.net.au/gardening/stories/s4063496.htm
Divide and Multiply	16/08/2014	Story	http://www.abc.net.au/gardening/stories/s4067682.htm
Heading Indoors	23/08/2014	Story	http://www.abc.net.au/gardening/stories/s4072380.htm
New Opportunities	6/09/2014	Story	http://www.abc.net.au/gardening/stories/s4081677.htm
Filling the Fence Line	20/09/2014	Story	http://www.abc.net.au/gardening/stories/s4090834.htm
A Hot Spot	11/10/2014	Story	http://www.abc.net.au/gardening/stories/s4104327.htm
Crazy for Tomatoes	25/10/2014	Story	http://www.abc.net.au/gardening/stories/s4113798.htm
Rock Minerals	1/11/2014	Story	http://www.abc.net.au/gardening/stories/s4119038.htm
Give Them Shelter	8/11/2014	Story	http://www.abc.net.au/gardening/stories/s4123980.htm
Water Plants	15/11/2014	Story	http://www.abc.net.au/gardening/stories/s4128179.htm
Flourishing Flowers	7/03/2015	Story	http://www.abc.net.au/gardening/stories/s4192476.htm
Seed bombs	4/04/2015	Story	http://www.abc.net.au/gardening/stories/s4210404.htm
Being Neighbourly	11/04/2015	Story	http://www.abc.net.au/gardening/stories/s4214031.htm
Stop the Stink	18/04/2015	Story	http://www.abc.net.au/gardening/stories/s4218196.htm
Compost v Mulch	2/05/2015	Story	http://www.abc.net.au/gardening/stories/s4227516.htm
Down-Pipe Planting	9/05/2015	Story	http://www.abc.net.au/gardening/stories/s4231312.htm
Bang for your Buck	16/05/2015	Story	http://www.abc.net.au/gardening/stories/s4235571.htm
Growing Greens	20/05/2015	Story	http://www.abc.net.au/gardening/stories/s4245304.htm
Climbing the Walls	23/05/2015	Story	http://www.abc.net.au/gardening/stories/s4239804.htm
Composting Gum Leaves	30/05/2015	Story	http://www.abc.net.au/gardening/stories/s4245311.htm
Tricky Spot	20/06/2015	Story	http://www.abc.net.au/gardening/stories/s4258137.htm
Pick and Plant	27/06/2015	Story	http://www.abc.net.au/gardening/stories/s4262430.htm
Delicious Climber	8/08/2015	Story	http://www.abc.net.au/gardening/stories/s4289427.htm
Passionfruit 101	22/08/2015	Story	http://www.abc.net.au/gardening/stories/s4297308.htm
Sunny Spot	5/09/2015	Story	http://www.abc.net.au/gardening/stories/s4306172.htm

Tomato Time	17/10/2015	Story	http://www.abc.net.au/gardening/stories/s4332116.htm
Productive Pots	24/10/2015	Story	http://www.abc.net.au/gardening/stories/s4337478.htm
Crop Rotation	31/10/2015	Story	http://www.abc.net.au/gardening/stories/s4342032.htm
Summers Coming	31/10/2015	Story	http://www.abc.net.au/gardening/stories/s4342022.htm

INTENTIONALLY BLANK PAGE