

Harvesting stormwater: testing the paradigm by assessing the impacts with an inter-disciplinary case study

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Abstract

Integrated Urban Water Management (IUWM) is often proposed as a framework for comprehensively managing the water cycle in urban areas. One of the tenets of IUWM is that, due to increased impervious area, stormwater runoff in excess of the natural flow could be captured and used to supplement the water supply, while mitigating the environmental impact. This thesis tests that theory through an inter-disciplinary case study utilising legacy data for the regional city of Ballarat, Australia. The case study approach has enabled the water balance of an urbanised catchment to be better understood in various ways and provided for five tightly nested research projects, being:

1. Does the long-term development of water management within a city provide insight into what drives decisions, therefore informing future progress?
2. Can the drivers of water use be adequately determined from a community wide, historical analysis such that future regulatory decisions can be informed?
3. Will assessment of the long-term streamflow of a river, combined with an urban water balance of the catchment, enable the identification of additional stormwater flow due to urbanisation, in excess of the natural flow?
4. Can the impact of urbanisation on groundwater be identified (i.e. trends quantified or qualified) from the city's legacy data or any available data sources, or models?
5. Is it possible to establish a comparative analysis technique that accounts for the uncertainty of information which changes over time, maintains intellectual rigour and is understandable and easily presented?

IUWM was found, perhaps unsurprisingly, to be a complex problem with the challenges being very contextual on the particular catchment and city being studied. This research revealed that evidence of greater volumes of water being generated from increasingly urbanised impervious catchments is not easy to find. This finding may challenge conventional thinking and means that decisions on stormwater harvesting and WSUD practices more broadly should first be informed by evidence of the water balance.

This research also revealed some very significant challenges in the water industry with finding and effectively using very dispersed data sets which are held and managed across multiple water agencies in various digital and hard copy formats. Information and data availability is critical to all aspects of IUWM, including in the measurement of its success, and so this research reminds the water industry of the importance of its data management practices.

Statement of authorship and originality

Except where explicit reference is made in the text of the thesis, this thesis contains no material published elsewhere or extracted in whole or in part from a thesis by which I have qualified for or been awarded another degree or diploma. No other person's work has been relied upon or used without due acknowledgement in the main text and the list of references of the thesis. No editorial assistance has been received in the production of the thesis without due acknowledgement. Except where duly referred to, the thesis does not include material with copyright provisions or requiring copyright approvals.

The following papers have been included as components of this thesis, and the co-author contributions are acknowledged.

	David Ebbs	Peter Dahlhaus	Andrew Barton	Harpreet Kandra
Ballarat's messy path to a water sensitive city: a long term investigation into water management of a city	80%	10%	-	10%
An unexpected decrease in urban water demand: making discoveries possible by taking a long term view	75%	10%	10%	5%
A water balance approach to investigate streamflow complexities downstream of an urban centre.	75%	10%	10%	5%
Impact of urbanisation on groundwater: piecing together hydrogeologic change through the historical development of a city	80%	15%	5%	-
Improving the decision making in complex situations: an Integrated Urban Water Management case study	75%	5%	15%	5%

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Table of Contents

Abstract.....	3
Acknowledgements.....	5
1. INTRODUCTION.....	15
1.1 Background	15
1.2 Aims and Objectives.....	17
1.3 Thesis structure.....	18
1.4 Contribution.....	21
2. LITERATURE REVIEW AND RESEARCH QUESTIONS	23
2.1 Water management in urban areas.....	23
2.2 Causal factors – Urbanisation and Climate Change	24
2.2.1 Extent of urbanisation	24
2.2.2 Impact of urbanisation on the water cycle.....	24
2.2.3 Impacts of climate change	25
2.2.4 Impact of impervious surfaces.....	27
2.3 Potential Solutions - Integrated Urban Water Management and alternative water supplies.....	28
2.3.1 Integrated Urban Water Management	28
2.3.2 Alternative Water Supplies	31
2.3.2.1 Distributed/decentralised stormwater capture and use	31
2.3.2.2 Centralised stormwater capture and use.....	32
2.3.2.3 Sewage recycling	34
2.3.2.4 Desalination of seawater.....	37
2.4 Extent of IUWM implementation.....	37
2.5 Barriers to stormwater use	38
2.5.1 IUWM economics.....	40
2.6 Modelling	41
2.7 Review Summary	42
2.8 Research Gaps	43

2.9	Research Questions.....	45
3.	METHODS.....	46
3.1	The appropriateness of a case study	46
3.2	The choice of a case study city	47
3.3	Scalability and transferability.....	50
3.4	Using secondary data.....	51
3.5	Modelling.....	53
3.5.1	Water Balance.....	53
3.5.2	Rainfall-runoff hydrologic modelling	54
3.5.3	Impact of farm dams	54
3.6	Boundaries of analysis	55
3.6.1	Place and time	55
3.6.2	Utilising annual stream flow	56
4.	BALLARAT's MESSY PATH TO A WATER SENSITIVE CITY: a long term investigation into water management of a city.....	58
4.1	Abstract	59
4.2	Introduction.....	60
4.3	Methods.....	61
4.3.1	Ballarat: a case study city	61
4.3.2	Water use: a common understanding	63
4.3.3	Data collection.....	63
4.4	Results	64
4.4.1	1850s–1920	68
4.4.2	1921–1940	68
4.4.3	1941–1980	69
4.4.4	1981–1999	70
4.4.5	2000–2015	70
4.5	Discussion	71
4.5.1	Development compared to the framework	72

4.5.2	Factors impacting decision making	72
4.6	Conclusion.....	73
4.7	Acknowledgements	74
5.	AN UNEXPECTED DECREASE IN URBAN WATER DEMAND: making discoveries possible by taking a long term view	75
5.1	Abstract	76
5.2	Introduction.....	77
5.2.1	Ballarat – A case study city	78
5.3	Methods.....	79
5.3.1	Data sources	79
5.3.2	Data management.....	79
5.4	Results and Discussion	81
5.4.1	Potable water use	81
5.4.2	Domestic and non-domestic use.....	81
5.4.3	Water use per person.....	84
5.4.4	Rainfall, water availability and restrictions	84
5.4.5	Outdoor water use versus total water use.....	87
5.4.6	Water price.....	89
5.4.7	Environmental awareness and water awareness programmes	92
5.4.8	Government and policy changes.....	92
5.5	Conclusions.....	93
5.6	Acknowledgements	94
6.	A WATER BALANCE APPROACH TO INVESTIGATE STREAMFLOW COMPLEXITIES DOWNSTREAM OF AN URBAN CENTRE	95
6.1	Abstract	97
6.2	Introduction.....	98
6.3	Method	99
6.3.1	Case study city: Ballarat.....	102
6.3.2	Water balance	104

6.3.3	Hydrologic response	105
6.3.4	Hydrologic model	106
6.3.5	Water from urbanisation due to impervious surfaces	107
6.3.6	Rainwater tanks	108
6.3.7	Land use change.....	108
6.3.8	Farm dams – depression storage	109
6.3.9	Baseflow.....	110
6.4	Results	110
6.4.1	Water Balance.....	111
6.4.2	Hydrologic response	111
6.4.3	Hydrologic model results.....	113
6.4.4	Water from urbanisation.....	113
6.4.5	Rainwater tanks	113
6.4.6	Impact of farm dams and depression storage.....	115
6.4.7	Baseflow.....	115
6.4.8	Relativity of impacts	115
6.5	Discussion	117
6.6	Conclusions.....	118
6.7	Acknowledgements	118
6.8	Addendum to Chapter 6 - Comparison of cities	119
6.8.1	Water use.....	119
6.8.1.1	Drivers of water use	123
6.8.2	River flow	126
6.8.2.1	Bendigo.....	126
6.8.2.2	Melbourne.....	128
6.8.3	Conclusions.....	134
7.	UNDERSTANDING URBAN GROUNDWATER BASEFLOW: piecing together hydrogeologic change through the historical development of a city	135
7.1	Abstract	136
7.2	Introduction.....	136

7.2.1	Landscape setting	138
7.2.2	Data sources	143
7.2.3	Watertable Ratio	144
7.3	Results	145
7.3.1	Basalt Aquifer	146
7.3.2	Upper Tertiary Aquifer	148
7.3.3	Quaternary Aquifer	149
7.3.4	Basement Aquifer	151
7.3.5	Catchment as importer or Exporter	152
7.3.6	Recharge or topography controlled	152
7.3.7	Groundwater extractions	153
7.4	Discussion	155
7.5	Conclusions	157
8.	IMPROVING THE DECISION MAKING IN COMPLEX SITUATIONS: an Integrated Urban Water Management case study	159
8.1	Abstract	160
8.2	Introduction	161
8.3	Assessment Tools	162
8.3.1	Economic Assessment	162
8.3.2	Multi-Criteria Decision Matrices	163
8.3.3	Triple Bottom Line or Sustainability Analysis	164
8.3.4	SWOT Analysis	164
8.3.5	Risk Management	165
8.3.6	STEEPLE Analysis	166
8.4	A modified technique	167
8.4.1	The Strategic Assessment Triangle	167
8.4.2	The Opportunity Portfolio Map	169
8.5	Results	170
8.5.1	Case Study	170

8.5.2	STEEPLE Analysis for alternative water supply options	175
8.5.3	Mapping STEEPLE results to the Strategic Assessment Triangle.....	186
8.5.3.1	Social Licence assessment of alternative water use options	186
8.5.3.2	Capability assessment of alternative water use options	186
8.5.3.3	Economic assessment of alternative water use options.....	189
8.5.4	Strategic Assessment Triangle scores for alternative water supply to Ballarat 190	
8.5.5	Opportunity Portfolio Map for alternative water supply to Ballarat	191
8.5.6	Alternative water supply option assessment.....	192
8.6	Discussion	194
8.7	Conclusions.....	195
9.	DISCUSSION	197
9.1	What are the lessons for water management from this research?	197
9.1.1	Urban Water Use	197
9.1.2	Price sensitivity of water demand.....	198
9.1.3	Stormwater as an alternative supply	199
9.1.4	Peri-urban development.....	200
9.2	Water monitoring, data availability and IUWM	201
9.2.1	Monitoring requirements for IUWM	201
9.2.2	Current monitoring	202
9.2.3	Required changes.....	203
9.2.4	Enabling the change	204
9.3	Secondary Data.....	204
9.3.1	Water information in Victoria	205
9.3.2	Issues with information sharing.....	206
9.3.3	Using secondary data	207
9.4	Evolution of Integrated Urban Water Management.....	207
10.	CONCLUSIONS.....	212
11.	REFERENCES	215

List of Figures

Figure 3.1- Ballarat and surrounding catchment basins.	49
Figure 4.1- Urban Water Management Transitions Framework (source: Brown et al., 2009)	60
Figure 4.2 - Ballarat and surrounding catchment basins	62
Figure 4.3 - Ballarat Water Consumption 1855–2015.	66
Figure 4.4 - Ballarat Water Supply and Domestic Connections 1905–2015.....	67
Figure 5.1 - Ballarat water use 1882–2016.....	83
Figure 5.2 - Ballarat water use per person versus rainfall anomaly.....	86
Figure 5.3 - External and internal domestic water use in Ballarat.	88
Figure 5.4 - Ballarat water consumption versus price.....	91
Figure 6.1 - Procedure for calculation the impacts of urbanisation on downstream river flow	101
Figure 6.2 - Ballarat location, water basins and transfers.....	103
Figure 6.3 - Yarrowee River flow and annual average hydrologic response	112
Figure 6.4 - Predicted and actual runoff anomaly and baseflow by year	114
Figure 6.5 - Annual average flow of the Yarrowee River and impact on flow of various causes.	116
Figure 6.6 - Annual water use in Melbourne, Ballarat and Bendigo	121
Figure 6.7 - Annual per capita water use in Melbourne, Ballarat and Bendigo.....	122
Figure 6.8 - Melbourne per capita water use versus water price	124
Figure 6.9 - Melbourne and Ballarat sewer flow as a percentage of water supply	125
Figure 6.10 - Yarrowee River and Bendigo Creek annual flow.....	127
Figure 6.11 - Merri Creek annual flow at Craigieburn.....	129
Figure 6.12 - Yarra River annual flow at four locations.....	131
Figure 6.13 - Difference in Yarra River annual flow at Warrandyte and Templestowe	132
Figure 6.14 - Difference in Yarra River annual flow at Templestowe and Fairfield.....	133

Figure 7.1: a) Yarrowee River catchment showing the Yarrowee River and an outline of the Ballarat urban area, b) the aquifer systems within the Yarrowee River catchment – basement (white), deep leads (pink), basalt (purple) and quaternary (green) and c) Aquifer relationship diagram adapted from (SKM, 2012)	140
Figure 7.2: Ballarat region as depicted by Eugene von Guerard prior to European settlement and mining (vonGuerard, 1854), and photographic evidence of the impact of mining (SLV, 1870).....	141
Figure 7.3: Baseflow of the Yarrowee River excluding sewage treatment plant discharge .	143
Figure 7.4: a) bores within Ballarat West basalt and b) groundwater level of discrete observations and monitored bores	147
Figure 7.5: a) location of bore 47192 within the deep leads and b) Groundwater level and rainfall anomaly.....	149
Figure 7.6: a) Quaternary aquifer and bore location and b) groundwater level with trends and averages and comparative Yarrowee River elevation.	150
Figure 7.7: a) location of constructed bores within the Basement Aquifer adjacent to the Yarrowee River and b) groundwater level of discrete and continuously monitored observation records.....	151
Figure 7.8: Bore construction frequency in the Yarrowee River catchment (excluding investigation and monitoring bores).....	155
Figure 8.1 - Risk Management Process (from ISO31000:2009).....	166
Figure 8.2 – Example Opportunity Portfolio Map.....	170
Figure 8.3 – Opportunity Portfolio Map for alternative water supply options to Ballarat	192

List of Tables

Table 1.1 – Publication Status	19
Table 1.2– Conference publications and presentations (peer-reviewed) from the research .	20
Table 2.1 - Distributed Stormwater Capture and Use	32
Table 2.2 - Centralised Stormwater Capture and Use	34
Table 2.3– Sewage recycling systems for potable supply (Source – (Khan, 2013))	36
Table 2.4 – Degree of integration of different model types	42
Table 4.1 – Factors impacting water use decisions	73
Table 7.1 – <i>River flow and recharge rate for Yarrowee catchment</i>	152
Table 7.2 – Indicative Water Table Ratio for three aquifers	153
Table 8.1– Transforming STEEPLE Analysis to the Strategic Assessment Triangle	168
Table 8.2 – Alternative water supply options for Ballarat.....	172
Table 8.3 - Stormwater collected locally for non-potable use	176
Table 8.4 - Stormwater with Managed Aquifer Recharge for non-potable use	177
Table 8.5 - Stormwater for potable use – above ground storage	178
Table 8.6 - Stormwater for potable use - Managed Aquifer Recharge	179
Table 8.7 - Rainwater tanks.....	180
Table 8.8 - Recycled wastewater for non-potable purposes.....	181
Table 8.9 - Recycled wastewater for indirect potable use	182
Table 8.10 - Recycled wastewater for direct potable use	183
Table 8.11 - Desalination.....	184
Table 8.12 - Superpipe	185
Table 8.13 - Social Licence Impact for IUWM implementation in Ballarat	187
Table 8.14 Capability to implement IUWM in Ballarat	188
Table 8.15 Alternative water supply cost ratings	190
Table 8.16 Alternative water supply social licence and capability ratings	191

1. INTRODUCTION

1.1 Background

With growing population, increasing standards of living creating demand for water and a changing climate impacting supplies, water stress is increasing throughout the world. Competing demands exist from agriculture, industrial requirements, domestic use and environmental needs. According to the United Nations, 2.6 billion people currently lack adequate supplies of clean water and sanitation (World Health Organization, 2015). It has been shown that 25% of cities with a population over 750,000 are currently suffering from severe water stress (McDonald *et al.*, 2014), and 80% are rated as vulnerable (Padowski & Gorelick, 2014). To help alleviate this, research and development activities are being pursued throughout the water industry.

Demand reduction is encouraged across all sectors. Domestically this includes education programs about optimal water use, pricing mechanisms for encouraging frugal water behaviour and the implementation of improved technology such as low flow shower heads and dual flush toilets (Grafton *et al.*, 2011; Melbourne Water, 2017a; Nieswiadomy, 1992). Industrial programs may include fit for purpose water consumption and efficiency programs (Melbourne Water, 2017a). Agricultural water use remains the highest demand overall (Donnelly & Cooley, 2015; Maupin *et al.*, 2014), however, reductions have been achieved through initiatives such as crop selection, loss reduction programs including piping irrigation channels and precision agricultural techniques to ensure the optimum amount of water is applied to the right place at the right time (Cosgrove & Rijsberman, 2000; Maupin *et al.*, 2014).

Optimum water use is encouraged in some locations, with Australia being an example, where tradeable water rights ensure that available water goes to the highest value demand (Turrall *et al.*, 2005). There can however be some distortions due to this market-based approach, with domestic water users for example currently have a far greater willingness to pay than irrigators, despite the irrigators using the water for production while domestic use is consumptive and may therefore provide less long-term benefit to society.

Additional water sources are being pursued. Dams are being constructed in some countries with renewable energy from hydropower being the driving force in many cases, with the dams planned or under construction in 2015 calculated to significantly impact the stream flow in 21% of river basins throughout the world (Zarfl *et al.*, 2015). Where groundwater

resources have been exploited as a supply, the finite nature of the resource has been recognised with demand forecast to exceed supply during the next century (Taylor *et al.*, 2013). Desalination plants are becoming widespread to take advantage of the vast reserves of sea-water, however high energy use creates concerns (Aviram *et al.*, 2014; Global Water Intelligence, 2016; March, 2015). Other techniques including harvesting fog and dew have been trialled (Abdul-Wahab *et al.*, 2007; Clus *et al.*, 2008). The regular flow of wastewater can also be recycled to provide a source of fresh water (Burgess *et al.*, 2015; Holmgren *et al.*, 2015; Khan, 2013; van der Hoek *et al.*, 2016).

Extractions, storage, transfer and pollution of the water used all create an environmental impact. Streamflow regime is altered, groundwater storage changed and the quality of the water affected. This can lead to riparian damage, loss of habitat, erosion and a general reduction in waterway and environmental health (Arthington *et al.*, 2006; Fletcher *et al.*, 2007; Poff *et al.*, 1997; Poff *et al.*, 2009). Of particular concern are urban areas where worldwide, more than 50% of people currently live and 80% are forecast to live by the end of the century (United Nations, 2012).

Increased urbanisation leads to higher rates of stormwater runoff due to the greater area and connectedness of impervious surfaces. Higher density development and reduced green areas leads to the heat island effect, where urban areas can be several degrees warmer than the surrounding landscapes. Integrated Urban Water Management (IUWM) is proposed as a framework for comprehensively managing the water cycle in urban areas and mitigating these issues. Throughout this thesis, IUWM is used as terminology for a comprehensive, or holistic, approach to the management of urban water. While it is understood that IUWM can be used to represent specific management techniques, it was chosen as the phrase which best represents the broadest view and the present understanding of managing the complete urban water cycle.

Aspects of IUWM include:

- Green infrastructure - This is an overarching term for infrastructure and management techniques which utilise natural processes to enable development to occur while maintaining pre-development outcomes. They have developed in different regions and include Low Impact Development (LID), Best Management Practices (BMP), Water Sensitive Urban Design (WSUD) and Sustainable Drainage Systems (SuDS). Types of infrastructure include swales, bio-retention basins, buffer strips, rainwater tanks, ponds and lakes, wetlands and green roofs and walls.
- Improved amenity - Detaining and utilising the water within the urban area can also result in greener and more pleasant environments to live. Shade and lower

temperatures result as well as environments which are more visually pleasing that have been shown to have a positive impact on real estate prices.

- Urban drainage - Reducing the impact of flooding and mitigating the effect of high rainfall events is a primary objective of urban development. Rather than this resulting in simply larger drains, creative techniques such as the use of roadways or other public space as detention for heavy rainfall events is possible. The objective is to consider drainage as a component within the overall urban water system rather than as a discrete problem.
- Sewage treatment - Wastewater must be treated to ensure the quality and flow of the discharge does not negatively impact community health or the environment. As for drainage, sewage can also be considered as one component of the overall urban water system.
- Fit for purpose water use - It is known that less than 20% of urban water is required to be of potable quality (Arbon *et al.*; Grafton *et al.*, 2009; Jorgensen *et al.*, 2009; Nieswiadomy, 1992; Roberts, 2005; Schleich & Hillenbrand, 2009). The use of water of suitable quality for watering gardens and open public spaces and toilet flushing for example can significantly alter the urban water balance.
- Distributed water management - Since their development in the 19th century, urban water systems have been primarily based on large centralised water systems. This has allowed for economies of scale and consistent quality of the water supplied and treatment of waste. However, opportunities for capture and use of water and waste at more local levels can also significantly alter the urban water balance.

One of the tenets of IUWM is that, due to increased impervious areas, stormwater runoff in excess of the natural flow could be captured and used to supplement the water supply while mitigating the environmental impact this runoff causes. Studies of stormwater flow regularly assume this relationship. The ability to mitigate both the negative environmental impact and supplement the potable water supply has obvious appeal, however the use of stormwater remains relatively low. The background, development and understanding of this is considered more widely in the literature review, Chapter 2.

1.2 Aims and Objectives

Given the apparent benefits of using stormwater to supplement the water supply of a city, an objective of this thesis is to improve the understanding of why this is not adopted more widely. The assumption inherent in this is that increased urbanisation will lead to greater volumes of runoff and generate higher streamflows which can then be exploited. The future requirements of a city must be understood to determine if the additional stormwater is

adequate to make a significant difference. The environmental impacts of capturing and using stormwater must be considered to ensure unforeseen consequences are minimised. Consumer acceptance and regulatory and organisational implications must also be appraised as they will affect the ability to implement change in the management of urban water.

A review of the global literature on IUWM and its adoption has highlighted gaps and research questions, presented in Chapter 2, that have directed this research. To provide insight into these questions, a case study has been completed utilising the city of Ballarat, a large provincial city in south-eastern Australia. Further details and greater justification for this approach are found in the Methods section, Chapter 3. However, a case study of a city of 100,000 people can enable many interactions of the water cycle to be investigated and demonstrate principles for consideration to comparable cities throughout the world.

Given the multi-factorial nature of stormwater use, a multi-disciplinary approach is used. Historical data collection, economic analysis, a water balance approach and the ability to assess and compare opportunities are combined to provide a broad understanding of the implications of using stormwater to supplement the water supply of a city.

This paradigm of IUWM, that there is unrealised potential for harvesting stormwater which can supplement the water supply, is tested by:

- Challenging the conventional thinking regarding urban water development and the urban water balance;
- Using long term community wide data to enable improved understanding of urban water demand;
- Providing evidence of the impact of urbanisation on the downstream river flow relative to other causes of stream flow change; and
- Identifying disparate data sources to determine the impact of urbanisation on groundwater and stream baseflow

1.3 Thesis structure

The theory that there is unrealised potential for harvesting stormwater which can supplement the water supply is tested through research questions developed from a review of the global literature (Chapter 2). The core research has been formed around a deep and inter-disciplinary case study utilising legacy data for the regional city of Ballarat, Australia. More information and justification for the use of this case study and associated methodologies is presented in Chapter 3.

The research comprises of five tightly nested projects for which individual chapters have been developed. Each of these projects have been written as a journal article and submitted, or being prepared for submission, for peer review and publication. The publication status for each of these is presented in Table 1.1. A number of conference publications and conference presentations have also been completed from the research, and those which have been peer-reviewed are shown in Table 1.2.

Table 1.1 – Publication Status

Chapter	Title	Journal	Status
4	Ballarat’s messy path to a water sensitive city: a long term investigation into water management of a city	The journal of the Australian Water Association, 2(4) https://doi.org/10.21139/wj.2017.037	Published
5	An unexpected decrease in urban water demand: making discoveries possible by taking a long term view	Water Policy, 20(3), 617-630. https://doi.org/10.2166/wp.2018.096	Published
6	A water balance approach to investigate streamflow complexities downstream of an urban centre.	Urban water	Reviewed, revisions made (under 2 nd review)
7	Impact of urbanisation on groundwater: piecing together hydrogeologic change through the historical development of a city		Under preparation for review
8	Improving the decision making in complex situations: an Integrated Urban Water Management case study	Australasian Journal of Water Resources	Under review

Table 1.2– Conference publications and presentations (peer-reviewed) from the research

Title	Conference
The journey to a Water Sensitive City – a case study of Ballarat, Victoria, Australia *	Water Infrastructure & the Environment, 56th New Zealand Hydrological Society, 37th Australian Hydrology and Water Resources Symposium and 7th IPENZ Rivers Group, Queenstown, New Zealand, Nov 28 - Dec 2, 2016
Exploring a flow regime and its historical changes downstream of an urbanised catchment	WSUD 2018 and Hydropolis 2018, 10th International Conference on Water Sensitive Urban Design, Perth, Australia
Losing stormwater: 60 years of urbanisation and reduced downstream flow	WSUD 2018 and Hydropolis 2018, 10th International Conference on Water Sensitive Urban Design, Perth, Australia
Impact of urbanisation on groundwater and the downstream river: A Ballarat case study#	HWRS2018, 38th Australian Hydrology and Water Resources Symposium Melbourne, Australia, 3-8 December 2018

** This paper was shortlisted for the G.N Alexander medal for the best hydrology paper at a conference or within any Engineers Australia publication between December 2016 and October 2018*

#An extended abstract for this presentation was submitted and reviewed

A review of the historical use of water and water management within the city (Chapter 4) assists in understanding the demand and whether stormwater can become a significant element of the water supply. Comparing the actual development to a framework enables unique aspects to be identified, and the long-term focus has highlighted some unexpected results.

Alternative techniques to analyse historical, community wide water demand has enabled further analysis on what drove the observed changes (Chapter 5). A clear demonstration of economic drivers at the community scale is presented, confirming the results of prior research and providing insights into the importance of pricing mechanisms.

To identify the quantity of stormwater available, in addition to what would have occurred without development, an annual water balance is combined with catchment rainfall/runoff modelling, impacts of farm dam proliferation and estimations of other impacts on river flow.

The method employed to determine this, and the results of the case study are presented in Chapter 6. Aspects of this work was reproduced for other selected Victorian cities, so as differences in local water management arrangements were minimised as much as possible. Results from this work are included as an addendum to Chapter 6.

While the impact of urbanisation on peak flows is well researched with techniques being developed world wide to mitigate the damage caused, the changes to groundwater due to increasing impervious surfaces is less well understood. Chapter 7 presents an analysis of groundwater changes surrounding the city using existing data, including information from unconventional sources. This method may prove useful to other researchers wishing to understand groundwater changes in urban settings where data is sparse.

Together, these results have formed an analysis which test the assumption about using stormwater as an alternative, supplementary water supply. There are a range of options within IUWM for supplementing existing water supplies, and each of these has different barriers to implementation. Comparative analysis of options in complex situations is required in many situations and many techniques can be employed. Chapter 8 demonstrates a method which can be readily understood and applied by a wide audience, but which is based on the best analysis available and may be beneficial to the further development of IUWM.

Within the research literature on urban water management there is some discussion about the revolutionary nature of IUWM, and how significant change is required within the industry which is not happening at the pace considered necessary by some researchers and practitioners. As a study of urban water management over a long time period this thesis places current changes within a broader landscape. In addition to identifying the limitations and opportunities arising from this work, the discussion (Chapter 9) also places the work in an historical context, and makes the case for incrementalism as the best descriptor of change and reform in water management.

The body of research presented in this thesis has investigated the opportunity and implications of using stormwater to supplement the water supply of a city. Assumptions about consumption, runoff, river flow and groundwater have been tested using data from a developing city over 140 years. Conclusions for this research are presented in Chapter 10.

1.4 Contribution

There are several contributions from this thesis that will be of national and international interest regarding urban hydrology and the use of stormwater as an alternative supply. These include:

- Using disparate, cross-institutional data to test the paradigm that increased impervious surfaces will result in greater stormwater flow and finding that urban hydrology is much more complex than this assumption and a range of anthropogenic and natural factors must be considered when assessing available water. Increased impervious surfaces do not automatically result in greater volumes of annual downstream flow.
- Demonstrating that the development of water management is uniquely dependent on a city's historical development, institutional arrangements and climatic and geological conditions. While understanding can be shared, assumptions that cities will follow a best path may be simplistic.
- Confirming price elasticity of domestic water use at a community scale, highlighting that price mechanisms may be less important than previously considered, and showing the limitations of price as a control for non-discretionary water use. This finding warrants further investigation as using price to control water consumption is a growing trend but may not lead to the desired outcome.
- Developing and demonstrating a technique for linking a long-term water balance at a regional scale with hydrologic modelling, farm dam estimation, bulk transfers into and out of the catchment, and other water use. This enabled the causes of changes in river flow over time downstream of a city to be assessed.
- The use of sewer flow to estimate internal water demand for community wide, historical data. This approach was able to provide a level of understanding of domestic water use which has otherwise been achieved at a limited scale by the use of surveys or short term, localised monitoring programs.
- The use of unconventional data and information to develop a deeper understanding of changes to urban groundwater which enabled new insights into the aquifers responsible for providing baseflow and the impact of urbanisation without the requirement of undertaking extensive groundwater monitoring.
- Developing a technique for comparative analysis of complex problems which is rigorous, easily understood and allows for uncertainty but leads to improved consideration of alternatives. This provides an additional tool for improved IUWM decision making.

2. LITERATURE REVIEW AND RESEARCH QUESTIONS

Urbanisation has many impacts on the water cycle. Rivers are dammed to provide storage, deforestation and increasing impervious area alters the flow regime, surface and groundwater interactions are altered and pollution of the waterway increases due to direct discharge or runoff from the urban area. While many of these aspects have been considered throughout this thesis, the focus is on the ability of IUWM (and specifically stormwater runoff), to create enough additional water over the longer term to significantly impact the traditional water supplies.

2.1 Water management in urban areas

Global water stress is demonstrable in the actions cities have had to undertake to secure water supplies. For example, the Millennium Drought (1997 - 2009) resulted in many south eastern Australian cities implementing water restrictions to match supply and demand (Marsden & Pickering, 2006). Drought conditions in California required a similar response to reduce demand in 2015 (EPA California, 2015). More recently, in early 2018 Cape Town only avoided running totally out of water due to the severe reduction in use (Walton, 2018).

Groundwater, a common source of supply for many cities, was estimated to provide 35% of freshwater worldwide in 2012 (Chu *et al.*, 2013) and 20% in the United States of America (USA) (United State Geological Survey, 2015), with demand forecast to exceed supply during the next century (Taylor *et al.*, 2013).

The worldwide water use for domestic purposes increased sixfold over the 20th century compared to a threefold population increase (Cosgrove & Rijsberman, 2000). Showers, hot water availability, flushing toilets, washing machines and garden watering all contributed to this increase in demand, as did the reduction in the number of people per dwelling (Cheruseril & Arrowsmith, 2007; Worthington & Hoffman, 2006). There is a recognition that this cannot continue, and in some developed countries water use peaked and actually reduced over the past 30 years (Donnelly & Cooley, 2015).

Demand can be modified using technology and management strategies. Temporary restrictions are known to be a quick and cheap method for reducing demand, and can result in savings of between 8% and 33% depending on the restrictions imposed (Chong *et al.*, 2009) and water use may not increase to previous levels when restrictions are removed (vanRiel & Jayasooria, 2011).

While domestic use constitutes the major component of the water demand within a city, and domestic restrictions can both impact and be publicised widely, industry is also a significant

consumer of a city's water demand. In the USA during 2010, 43% of supplied water was for commercial and industrial purposes (Barber, 2014; Maupin *et al.*, 2014) while in Australia during 2012/13 water use in manufacturing was over 20% of the potable water supply (Australian Bureau of Statistics, 2013b).

Population is increasing, cities are growing larger, and in many cases, the supply from traditional sources is not expected to increase, or might decrease, due to changing climate. Alternative water supplies will be required by some cities to meet demand.

2.2 Causal factors – Urbanisation and Climate Change

2.2.1 Extent of urbanisation

Global population has increased dramatically over the past 200 years, and the rate of growth continued to increase up until the end of the 20th century. With higher survival rates, education and some controls, population growth has been slowing, although the United Nations predicts total population to continue rising throughout the 21st century (United Nations, 2018b). For the first time in human history, more than half the people live in urban areas, with a rise in megacities resulting in 19 cities in the world with over 13 million people in 2016 (United Nations, 2016). This urbanisation is predicted to continue, with 68% of people to live in cities by 2050 (United Nations, 2018a). Increasing urbanisation has been occurring since the Industrial Revolution with the specialisation of skills and the ability to perform tasks for others in the community resulting in greater efficiencies, increased standards of living and a reliance on the networks in cities.

As societies became more affluent during the 20th century, the number of people in each residence reduced, resulting in an even higher growth rate of housing and urban area. Another major impact on urban development over the past 150 years has been the motor car. The widespread use has resulted in significant areas of hard paved roads and car parks which has had a dramatic effect on the total impervious surfaces within an urban area.

2.2.2 Impact of urbanisation on the water cycle

The increase in population, urbanisation and associated impervious areas has multiple impacts on the water cycle. Higher demand results in greater extraction from rivers, and even when this is returned to natural waterways after use, the flow regime has been significantly altered. Inter-basin transfers relocate water between catchments. Pollution levels are inevitably higher after use, even where discharges are monitored and controlled, while leakage from infrastructure can result in unknown release of water and pollutants.

Stormwater is the highest source of some pollutants for many receiving waterways (Barbosa *et al.*, 2012; Stone Jr, 2004). Common forms of pollution from the urban environment include gross pollutants, heavy metals, hydrocarbons and pathogens. Sediments can be a problem alone, but also act as the carrier for many of these other pollutants (Pitt *et al.*, 1995).

Flood mitigation is a major focus in urban environments, often resulting in diversion of waterways and channelisation of streams. In addition to the direct effect, the flow regime of the receiving waterway, which has been shown to be a 'master variable' for stream ecology (Walsh *et al.*, 2012), is severely impacted.

Land use has significantly changed, both in the development of the urban area and surrounding agriculture required to provide food. There is an accompanying change in the water cycle due to vegetation usage, transpiration and runoff. The impact of altered runoff due to land use alteration was first documented in a seminal study by Meisinger in the 1920's (1922) where two similar catchment were studied over a 10 year period, with one having trees removed while the other was retained in its pristine state. The changes in landscape also result in a heat island effect (Arnfield, 2003) due to greater heat retention and lower transpiration.

As implied in a number of the issues identified, one of the most significant effects on streamflow in the urban environment is the replacement of natural surfaces with impervious pavement, and in particular where there is a continuous flow path to a stream, or directly connected imperviousness (Burns *et al.*, 2015).

2.2.3 Impacts of climate change

Climate change is expected to further impact water supply in many areas. Under climate change, surface and groundwater resources are expected to decrease significantly in sub-tropical regions, and drought events increase in dry regions (Jiménez Cisneros, 2014). Increasing temperatures are predicted to lead to higher evaporation and evapo-transpiration, leading to drier soils and higher water demand by plants (Macinnis-Ng & Eamus, 2009). Further, rivers that rely on glacial and snow melt are expected to experience greater flow variability (Pederson *et al.*, 2013).

Changes in climate can cause a greater change in water availability than the change in rainfall. For example, in Perth, Western Australia, the rainfall from 2000 – 2015 is 80% of the average rainfall from 1870 – 1970. However, as much of the rainfall evaporates or infiltrates the ground, the surface runoff to rivers is now close to zero and cannot be relied upon for water supply (Water Corporation, 2013). Similarly, in south-eastern Australia, changes in rainfall patterns which result in more precipitation in spring and summer lead to a higher

percentage in evaporation rate than winter falls. Meteorological organisations in many countries provide country specific information and updates on how climate is tracking. For Australia, much information can be found from <http://www.bom.gov.au/state-of-the-climate/>.

Reservoir storage requirements are determined by water usage, expected time between rainfall and natural storage such as snow and glaciers. Increasing time between rainfall events and a reduction in natural storage will result in higher man-made storage requirements if the same demand is to be met.

While the overall impact of climate change is known with higher temperatures and less frequent but higher intensity rainfall, detailed impacts of this are more difficult to estimate. The larger rainfall events may result in greater runoff occurring, creating an additional resource but also resulting in higher erosion for example, or the increased infiltration and evaporation may result in decreased runoff.

Impervious surfaces result in higher rainfall-runoff relationships than natural environments, with peak flows being estimated at over ten times greater from a paved surface (Fletcher *et al.*, 2007). The frequency of peak flows and number of downstream flow events is also higher as runoff occurs almost immediately following all but the smallest rain events (Burns *et al.*, 2011; Chu *et al.*, 2013; Walsh *et al.*, 2012). Conversely, no-flow events can also increase as less water infiltrates the soil and is not available for baseflow (Hamel *et al.*, 2013) although this is dependent on the catchment and the contribution that groundwater makes to the stream. The resultant impact this has on the morphology of receiving waterways and the riparian landscapes, has been well established (Fletcher *et al.*, 2012; Klein, 1979; Shuster *et al.*, 2005).

It has been shown (Poff *et al.*, 1997) that establishing minimum environmental flow and reducing peak flows is not an adequate response for the ecological health of the waterways. Any deviation from the natural flow regime will result in ecological changes (Arthington *et al.*, 2006). A number of flow characteristics must be achieved to maintain biodiversity and ecological health, including magnitude, duration, frequency, timing and rate of change (Fletcher, Vietz, *et al.*, 2014). There are a wide range of environmental impacts which can be measured to determine stream health and the impact of flow changes caused by urbanisation and water management. While establishing appropriate streamflow does not guarantee environmental health, '*ecosystem sustainability cannot be achieved without hydrologic restoration*' (Roy *et al.*, 2008).

In their discussion regarding protecting streams from stormwater runoff, Fletcher, Vietz, *et al.* (2014) state that stormwater harvesting should "*be designed to restore the frequency of runoff and overall flow volume*". They do however recognise that establishing pre-development flows can be challenging.

Research over a long period has shown varying results with regard to total annualised streamflow change due to urbanisation, identifying a decrease when groundwater contribution is significant (Otto *et al.*, 2002), little change (Wiitala, 1961) or a significant increase (Jones, 1971). Overall in Australia approximately 15% of rainfall reaches streams as runoff, the majority either evaporating or transpiring (Gill, 2011). In contrast, runoff in highly urbanised environments can be 90% (Environment Australia, 2002). Only 10% impervious area is required to have a noticeable effect on stream flow (Booth & Jackson, 1997).

2.2.4 Impact of impervious surfaces

Impervious surfaces result in higher rainfall-runoff relationships than natural environments, with peak flows being estimated at over ten times greater from a paved surface (Fletcher *et al.*, 2007). The frequency of peak flows and number of downstream flow events is also higher as runoff occurs almost immediately following all but the smallest rain events (Burns *et al.*, 2011; Chu *et al.*, 2013; Walsh *et al.*, 2012). Conversely, no-flow events can also increase as less water infiltrates the soil and is not available for baseflow (Hamel *et al.*, 2013) although this is dependent on the catchment and the contribution that groundwater makes to the stream. The resultant impact this has on the morphology of receiving waterways and the riparian landscapes, has been well established (Fletcher *et al.*, 2012; Klein, 1979; Shuster *et al.*, 2005).

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2.3 Potential Solutions - Integrated Urban Water Management and alternative water supplies

The recognition of the need for additional water supplies in conjunction with the knowledge of potential environmental concerns from urban runoff and the improved amenity a different approach to water management could bring has led to the idea that the water cycle can be managed in a more comprehensive manner. While this idea, with variations depending upon the circumstances, has been given a number of titles (e.g. Integrated Water Management, Integrated Water Cycle Management, Integrated Water Resource Management), throughout this thesis, with the emphasis on the urban water cycle, the comprehensive approach to the management of the water cycle is referred to as Integrated Urban Water Management (IUWM).

2.3.1 Integrated Urban Water Management

IUWM offers multiple benefits that span improved amenity in the lived environment, better environmental outcomes for receiving waterways and additional water resources that can supplement, or even replace, current supplies. While integration of the water cycle has been recognised and discussed for over 60 years (Angelakis & Xiao, 2015; Argue & Barton, 2007; Biswas, 2004), increasing urbanisation and demand on existing potable water supplies (McDonald *et al.*, 2014) have refocussed attention to the particular needs of cities.

Water Sensitive Urban Design (WSUD) was developed in Australia in the early 1990's as a way of managing the complete water cycle more holistically (Lloyd, 2001). It involved managing stormwater at the source, utilising alternative water sources and management of the integrated urban water cycle in the same manner as prescribed by IUWM. It has become more common for WSUD to now describe alternative drainage options to the traditional kerb and channel approach of removing water as quickly as possible from the urban environment. This includes rainwater tanks, buffers, swales, bio-retention basins, ponds, lakes and

wetlands. The slowing of water from the urban areas positively impacts the downstream waterway, while providing water for an improved lived environment.

Similarly, the impact of high stormwater flows from urban areas on the surrounding rivers in the USA led to the development of stormwater best management practices (BMPs). King George's County, Maryland led the way with the introduction of low impact development (LID) guidelines that reduce peak flows and pollutant loads to rivers (United States EPA, 2000).

The damage caused by high flows through combined sewer outfalls in the United Kingdom (U.K.) led to similar principles and solutions being adopted (Fletcher, Shuster, *et al.*, 2014). They were named sustainable urban drainage systems (SUDS), and are now more commonly called SDS, or SuDS, in the recognition that it can apply to non-urban areas. The similarities between WSUD, LID and SuDS and the motivations for each are described by Fletcher, Shuster, *et al.* (2014), who found the terms interchangeable at a practical level. The nature of solutions which manage stormwater at the source is consistent with the philosophy that distributed systems are inherently more sustainable, robust, increase community awareness and involvement (Biggs *et al.*, 2008) and are therefore aligned with a path towards integrating the urban water cycle (Ward *et al.*, 2012).

Despite the implementation of these 'at source' techniques for at least 15 years (United States EPA, 2000), there are concerns. Ongoing maintenance and lifetime costs are critical. It has been reported that on first inspection, 90% of installations had not received adequate maintenance, and training and information was required to ensure this was undertaken (Lord & Hunt, 2012).

While WSUD has been shown to reduce peak and overall flows to receiving waterways, making the retention of pre-development flow regime a possibility, while also reducing pollutants, heavy rain events may still require peak flow bypass and downstream traditional drainage (Melbourne Water, 2005). This means that both traditional pipe and gutter schemes may be required along with WSUD, resulting in higher costs (Chocat *et al.*, 2007). Despite concerns and difficulties with implementation it is becoming more widespread and accepted within the industry (Bettini *et al.*, 2012), although higher initial and ongoing costs are barriers to widespread use. Implementation often occurs only when traditional stormwater management would be unacceptable (Argue & Barton, 2007).

In addition to improved drainage, WSUD also offers opportunity for stormwater use, and thus meet the objectives of IUWM. Swales and buffer zones are naturally watered with stormwater runoff reducing demand on potable supply, while storage such as rainwater tanks and wetlands can be used to provide water substituting for the current supply. This is most commonly with a fit for purpose use, such as toilet flushing and garden watering, and in the

case of community wide scheme, via a 'third-pipe' which provides a non-potable water source, generally at a reduced cost to encourage use.

As WSUD has focussed on managing drainage, runoff and environmental impact it may not be considered comprehensive, and there is a large gap between the increased use of WSUD as a way of managing stormwater runoff with some additional benefits of reduced demand on supply, and full integration of the water supply as envisioned by IUWM. It has been estimated that less than 5% of stormwater is used in Australia (Dillon *et al.*, 2004), although as much of this is done locally without metering, the exact quantity is unknown, and since the end of the Millennium Drought, the quantity may have in fact decreased (Melbourne Water, 2015). To achieve substantive change in the way water is managed and full integration of the urban water cycle, some researchers believe requires a difference in the way the urban water cycle is managed (Daniell *et al.*, 2014).

Systems theory reminds us that the overall system cannot be optimised by optimising individual elements (Skyttner, 2005). It is possible that concentrating on elements of the integrated urban water cycle will not result in the overall objective being met and the water cycle must be considered comprehensively.

One widely used term for the vision of an integrated urban water cycle is the water sensitive city (Brown *et al.*, 2008) which includes increased urban amenity, reuse of water, reduced heat island effects, lower demands on existing water supplies and a reduction of waste streams. However, as with many complex issues such as the urban water cycle, implementation is difficult (Brown, 2005; Camilleri & Trowsdale, 2012; Roy *et al.*, 2008), although some researchers believe this is due to satisfactory progress and the adequacy of current water management and decision making (Marsden & Pickering, 2006). A barrier to IUWM that is commonly cited is the institutional arrangements of water management (de Haan *et al.*, 2014; Ferguson *et al.*, 2012; Livingston, 2008; Moglia *et al.*, 2011). Separate organisations responsible for resource management, distribution of potable water supplies, sewage collection and treatment, drainage, flooding, groundwater and catchment management makes coordination of IUWM activities difficult. Even with the best intentions, the boundaries of responsibility and available funding create barriers for organisations trying to manage across the water cycle. It has been shown that this can be best achieved when an established informal network is in place (Bettini *et al.*, 2012) so that relationships between stakeholders enables action between organisations.

The objective of the Water Sensitive City is to be part of a sustainable environment. If the environment around the city is to return to or remain in the condition established as the most ecologically sound, the city itself must operate as closely as possible to a closed system within the environment, providing its own water.

This thesis explores the implications and possibility for a 'closed' water system. It will not of course be a fully closed system. Precipitation brings water from outside the city boundaries and groundwater, evaporation and any discharge may still leave. The conceptualisation of a city with a 'closed' water boundary is one where there is no net surface or groundwater extraction from outside the city boundary, and the water leaving the boundary would be equivalent to pre-development flow, and this thesis further explores the implications and possibility of this occurring. Catchments which collect water for cities are fixed in size. To increase collection, catchments further from the city must be utilised. Alternatively, the 'city as catchment' will automatically increase in size as the footprint of the city increases, leaving natural catchments surrounding the city as they were pre-development. The impervious surfaces will also result in runoff from low rainfall events, as distinct from natural catchments where a significant portion of water infiltrates the surface or is transpired from vegetation.

2.3.2 Alternative Water Supplies

Within the broad framework of IUWM, there are a number of opportunities for water supplies to supplement or replace traditional surface water and groundwater. These include distributed stormwater capture and use, centralised stormwater capture and use, recycling treated sewage and desalination of seawater. While desalination may not meet the environmental and system objectives of IUWM, in a comparison of alternative water supply options for a city it must be included. Each of these potential supplies is discussed, including a description of how widely they have been implemented currently.

2.3.2.1 Distributed/decentralised stormwater capture and use

Distributed stormwater capture and use includes options at the lot scale (rainwater tanks) to community scale storage and distribution through a local 'third pipe' scheme. There are a range of technologies currently available for distributed water systems and the role they play in developing sustainable communities which are described by Makropoulos and Butler (2010). The attributes and concerns about distributed stormwater capture and use are summarised in Table 2.1 which has been compiled from a range of references (Akter & Ahmed, 2015; Biggs *et al.*, 2008; Mitchell *et al.*, 2003; Mitchell *et al.*, 2002; Naiman, 2014; Philp *et al.*, 2008; Spies & Dandy, 2013; Zhang *et al.*, 2009). While the current stormwater substitution of potable supply is low, this will inevitably increase if supply becomes restricted. The needs of the city will therefore determine the amount of stormwater use. Use of the water to replace potable supply occurs when possible, but is limited by the amount of storage available in the distributed system.

Table 2.1 - Distributed Stormwater Capture and Use

Positives	Negatives
<ul style="list-style-type: none"> ● 80% of water use is non-potable ● Produces fit for purpose water ● Enhances and supports local environments ● Connects community to the environment ● Water reuse as required ● Smaller individual investment ● Stormwater reuse for non-potable applications is well accepted 	<ul style="list-style-type: none"> ● Cost of two water supplies ● Potential for cross contamination ● Distributed systems are less controlled ● Distributed storage will not meet all water demand ● Land for treatment and storage is likely to be of high value ● City requirements determine water reuse, so environment gets remainder ● External reuse is weather and seasonal dependent, and out of phase with supply

2.3.2.2 Centralised stormwater capture and use

The 'city as catchment' could supply water to bulk storage which could be treated and supplied into the existing distribution system. A centralised system naturally addresses many of the issues associated with distributed systems, but raises alternative concerns which are summarised in Table 2.2.

For example, Singapore, which has a fresh water scarcity issue due to a relatively small land area for capture and storage (Philp *et al.*, 2008), is one of the few countries to utilise stormwater for supply (PUB, n.d.). California recognised that capturing stormwater and transferring this via infiltration to groundwater storage was the most efficient method to supplement the supply to Los Angeles, with rainwater tanks and distributed storage to be used where infiltration was not an option (Naiman, 2014). As the streamflow into reservoirs in Perth, WA reduced by more than 80% in 2006 – 2012 compared with the long term average (Water Corporation, 2013) alternative supplies were required. Now, over 45% of supply is from groundwater rejuvenated by stormwater infiltration, with 45% from desalination of seawater. On a smaller scale, Orange, NSW, Australia, captures and treats stormwater to

supplement the potable supply (Orange City Council, n.d.), while Wannon Water, a water authority in south western Victoria, Australia have implemented a roof water harvesting scheme in Warrnambool which also supplements the town water supply (Wannon Water, 2011). Finlayson et al. (2015) identified that centralised capture and use of stormwater is an option in Melbourne's western region as wastewater and stormwater flows exceeded the demand after allowing for environmental requirements.

One of the drivers for distributed water systems is to minimise the reliance on large, and therefore inflexible, infrastructure. Creating large stormwater storage is therefore directly counter to this, even though the objectives are the same. If a centralised system is to be used effectively, then large storage will be required. Two methods for this, managed aquifer recharge and above ground storage, are generally proposed. The issues associated with these are summarised in Table 2.2.

Table 2.2 - Centralised Stormwater Capture and Use

Positives	Negatives
<ul style="list-style-type: none"> ● Adequate storage to enable high levels of reuse ● Effective control of the water source ● Single water supply infrastructure ● Potential to establish predevelopment flows in river currently supplying city ● Pollutants and erosion controlled in the downstream river 	<ul style="list-style-type: none"> ● Treated stormwater must be accepted as an alternative supply (although fit for purpose water could be supplied with more infrastructure) ● Large single investment ● Less community involvement ● No impact on flooding and local waterways within the city
<p><u>Managed aquifer recharge</u></p> <ul style="list-style-type: none"> ● Use of existing natural storage reduces cost ● Aquifer has potential to provide some treatment ● Long period between charging and use may increase acceptability ● Natural treatment possible 	<ul style="list-style-type: none"> ● Suitable aquifer is required ● Transfers within the aquifer must be considered ● Treatment may be required before and after charging
<p><u>Above ground storage</u></p> <ul style="list-style-type: none"> ● Well understood ● Lakes can provide amenity 	<ul style="list-style-type: none"> ● Not suitable for coastal cities ● Affects land use of dammed area ● Management of discharge flow regime is required to maintain river ecological health ● Evaporation losses

2.3.2.3 Sewage recycling

As a significant stream in the urban water balance, the reuse of water from treated sewage would significantly reduce the requirement for fresh potable supplies. The logic driving stormwater use, a waste which currently may cause environmental damage can be used as

a resource, is also true for recycling sewage. Although there is variation in sewage flow at times of heavy rain due to inflow and infiltration, a base level of use is essentially independent of rainfall. The majority of sewage is treated in centralised plants which are recognised to provide greater controls, even amongst proponents of decentralised systems (Sharma *et al.*, 2010).

The issue which limits sewage reuse is contamination. Human waste contains pathogens which are responsible for many community concerns, including the 'yuck' factor, which can result in strong social resistance to recycling (Hurlimann & Dolnicar, 2010). Metal contamination can be a significant problem, with major sources being metal pipework, roofing and trade waste. An increasing and serious problem is the contaminants associated with by-products of both legal and illegal pharmaceuticals (i.e. drugs). Salt levels, from urine, groundwater infiltration in some circumstances and trade waste must also be managed. If contaminants are not removed effectively from the system the increasing concentration of these that will result from recycling is a significant concern for any sewage reuse management.

Recycled water from sewage can be used as either fit-for-purpose water, which may substitute for potable supply, or treated to a suitable level and added to the supply. Typical uses for fit-for-purpose water are agricultural irrigation, industrial water, watering of golf courses and public open spaces, or community use schemes such as a third pipe non-potable supply. Recycled water could also be used for environmental purposes, replacing water removed from rivers due to urban demand, however, the contaminant levels and flow regime need to be carefully managed to ensure that the desired environmental outcome is achieved. As there is no direct economic benefit in many jurisdictions for supplying environmental water, the cost of treating water to an acceptable level to replace the river flow can be a significant barrier.

Reuse of recycled water overcomes one of the major economic barriers to recycling – the additional distribution system required for fit-for-purpose water, or the co-location of demand with supply. Two pathways exist for recycled water into the potable system – direct and indirect potable reuse. Direct potable reuse involves injection of treated water into a storage reservoir or the distribution network upstream of a treatment plant. Indirect potable reuse takes advantage of an environmental water body such as a lake, river or aquifer. This can provide additional purification, dilution and time between the injection and use of the water. There are an increasing number of potable reuse schemes for sewage throughout the world. A sample of these sourced from a report into the use of sewage as a potable water supply by the Australian Academy of Technological Sciences and Engineering (Khan, 2013) are listed in Table 2.3.

Table 2.3– Sewage recycling systems for potable supply (Source – (Khan, 2013))

Project Location	Project Size (ML/day)	Initiation (year)	Type of Reuse
Montebello Forebay, CA, USA	165	1962	Indirect
'Old' Goreangab Water Reclamation Plant, Windhoek, Namibia	7	1968	Direct
Water Factory 21, CA, USA	60	1976	Indirect
Upper Occoquan Service Authority, VA, USA	204	1978	Indirect
Hueco Bolson Recharge Project, TX, USA	38	1985	Indirect
Clayton County, GA, USA	66	1985	Indirect
West Basin Water Recycling Plant, CA, USA	47	1993	Indirect
Gwinnett County, GA, USA	227	1999	Indirect
Scottsdale Water Campus, AZ, USA	53	1999	Indirect
Toreele Reuse Plant, Wulpen, Belgium	7	2002	Indirect
'New' Goreangab Water Reclamation Plant, Windhoek, Namibia	21	2002	Direct
NEWater, Bedok, Singapore	86	2003	Indirect
NEWater, Kranji, Singapore	55	2003	Indirect
Alimos Barrier, CA, USA	10	2005	Indirect
Chino Basin Groundwater recharge Project, CA, USA	69	2007	Indirect
Groundwater Replenishment System, Orange County, CA, USA	265	2008	Indirect
Loudoun County, VA, USA	42	2008	Indirect
Arapahoe County/Cottonwood, CO, USA	34	2009	Indirect
NEWater, Changi, Singapore	230	2010	Indirect
Prairie Waters Project, Aurora, CO, USA	190	2010	Indirect
Groundwater Replenishment Trial, Perth, Australia	5	2010	Indirect
Cloudcroft NM, USA	0.1	2011	Direct
Beaufort West Municipality, South Africa	1	2011	Direct
Dominguez Gap Barrier, Los Angeles, CA, USA	10	2012	Indirect
Raw Water Production Facility, Big Spring, TX, USA	7	2013	Direct

These projects demonstrate that indirect potable reuse is the preferred technology, although three direct potable schemes have been constructed in the USA and South Africa in recent years. Prior to this, this only direct potable reuse scheme had been in Namibia, where it has been operating since the 1960's. The number and size of the projects has increased over time, consistent with the need to respond to increasing demand on the traditional water supplies.

2.3.2.4 Desalination of seawater

Desalination provides an effectively never-ending supply of fresh water. As over 50% of the world's population live in large cities, and 75% of these are within 60km of the coast (Aviram *et al.*, 2014), sea-water has significant attractions as an alternative water source. However it has high infrastructure and operating costs, and requires more energy than other water sources (Knights *et al.*, 2007), although the energy cost of Reverse Osmosis, the preferred technology in the majority of desalination plants, has reduced significantly over the past decade (March, 2015). The costs presented in the review by March (2015) span a wide range, and the choice of desalination to produce potable water is obviously dependent upon the circumstances of the city at that time, however it can be summarised as producing high quality water with none of the concerns of recycled sewage or stormwater, but at a high energy and financial cost. In June 2015, the International Desalination Association estimated there to be over 18,400 plants operational through 150 countries (International Desalination Association, n.d.), although these only provided water to an estimated 1% of the world's population (Global Water Intelligence, 2016).

2.4 Extent of IUWM implementation

As discussed throughout this review, there have been some cities with significant implementation of various aspects of IUWM. Those cities with adequate aquifers or which currently rely on groundwater can relatively easily divert stormwater to these storages. In Perth, Western Australia, groundwater with stormwater infiltration is supplying about 45% of the potable requirements (Water Corporation, 2013). A similar scheme is being implemented in Los Angeles, California (Naiman, 2014), and Managed Aquifer Recharge of stormwater is underway in Adelaide, South Australia (Dillon *et al.*, 2014). However 65% of cities throughout the world rely on surface water supply (Chu *et al.*, 2013). Many of these have large natural storages such as snow or glaciers. While these stores are under threat from climate change and glacial retreat (Li *et al.*, 2011) and the issue of requiring alternative water supplies is becoming very real, IUWM has not yet been comprehensively implemented.

Similarly, cities that have implemented sewage recycling have been highlighted. The frequency of this is increasing, although the total number is still negligible compared with the overall water supply, and community concerns are significant (Hurlimann & Dolnicar, 2010).

While the use of stormwater management techniques to prevent high peak flow has become more widespread, the reuse of stormwater is minimal. For example, Melbourne Water had active stormwater licences for 1,855 ML in 2013/14 which was less than 0.5% of the total water supply (Melbourne Water, 2015), although some small and domestic reuse schemes would have been unlicensed and therefore not counted. However, to supplement supplies Melbourne installed a reverse osmosis desalination plant which was the world's largest at that time (March, 2015) with a capacity of 150 GL/year (Melbourne Water, 2015). This leads to researchers such as Marlow et al.(2013) asking 'Why is Sustainable Urban Water Management so strongly supported in the literature, but not so widely adopted?' and they conclude that conservative decision making by regulatory authorities is reasonable given their circumstances.

Where stormwater use has been implemented, it is almost always for non-potable uses such as garden watering or parkland irrigation, toilet flushing and clothes washing. Information from a number of Australian studies (Beal & Stewart, 2011; Grafton, 2013; Melbourne Water, 2015; Roberts, 2005; vanRiel & Jayasooria, 2011) indicate that only about 20% of a city's demand is for potable water with the remainder able to be met from 'fit for purpose' sources. It is also consistent with the 'Australian Guidelines for Water Recycling' which recommend that stormwater is used for non-potable applications (NRMCC, 2004).

Despite stormwater capture and use being recognised as being both an alternative supply and positively impacting the environment, the use is very low. It is worthwhile then to consider the barriers to stormwater use more fully.

2.5 Barriers to stormwater use

A study of the opinions of 1200 Australians showed that while acceptance of stormwater use is high for external and non-drinking sources, less people are comfortable with using it as a drinking supply (Fielding *et al.*, 2015), although it has higher acceptance than treated wastewater use (Mankad *et al.*, 2015). This may in part be due to untreated rainwater directly from tanks being the only alternative drinking supply considered.

A number of studies indicate that community acceptance, institutional organisation and legislative difficulties are known to be some of the social barriers to the use of stormwater as an alternative supply. In their assessment of impediments to sustainable urban stormwater management, Roy et al., (2008) identified the following seven barriers to implementation,

consistent with those described by other researchers within this area (Brown, 2005; Camilleri & Trowsdale, 2012; de Haan *et al.*, 2014; Floyd *et al.*, 2014; Livingston, 2008).

1. Uncertainties in performance and cost
2. Insufficient engineering standards and guidelines
3. Fragmented responsibilities
4. Lack of institutional capacity
5. Lack of legislative mandate
6. Lack of funding and effective market incentives
7. Resistance to change

While there may be some economic and technical issues associated with these factors, all of them can at least partially be attributed to organisational, societal or legislative concerns.

As with all alternative water use schemes community acceptance is an issue for stormwater use. The same authors identified the following nine factors for acceptance of stormwater use.

1. Fair distribution
2. Trust in technology
3. Environmental Impact
4. Costs
5. Loss/wastage of stormwater if not used
6. Future water security
7. Consistent water quality
8. Education
9. Perceived effectiveness of the scheme

To understand their perception of risk of alternative water supplies, practitioners within the water industry were surveyed (Dobbie & Brown, 2012). They believed stormwater treatment and use had less risk than other alternatives (wastewater re-use and desalination), and the greatest area of risk was water cost. People within an industry may be more aware of, and therefore comfortable with, the technology and risks associated with alternative solutions than the general public.

Rijke *et al.*, (2013) identified that a critical factor in transitioning toward a Water Sensitive City was the interaction of government institutions, with both formal and informal connections necessary. A study by de Haan *et al.* (2014), discussed how all transitions need to meet existence, relatedness or growth needs, and that moving to a Water Sensitive City was able to meet some growth and relatedness needs. The difficulties in implementing the vision of a Water Sensitive City are also discussed by Camilleri and Trowsdale (2012).

2.5.1 IUWM economics

In Australia, water is a tradeable commodity, a strategy which is intended to ensure that the most economic use and source of water is chosen (National Water Commission, 2011). While allocations are made for environmental flows, the social and environmental effects become secondary to the economic decisions for which water companies are responsible. These are externalities which have not been fully quantified, therefore distorting the economic decision making process (Wentworth Group of Concerned Scientists, 2016; Young, 2014). Transferring water between basins can assist with optimal allocation, but it does not create any additional resource, and can result in disillusionment from those within the basin supplying water (Nathan, 2004).

Many published studies from Australia, where the issue has been considered for some time, have investigated the economics of stormwater as an alternative water supply. Individual rainwater tanks have been shown to be expensive, and while costs can be reduced by the use of community or development schemes with up to 1000 residences, they are still generally more expensive than centralised water distribution systems (Wilson *et al.*, 2013). As the responsibility for operation and maintenance of tanks generally lies with the resident, there are concerns with the ongoing performance. A study in Melbourne indicated that of 417 tanks inspected there were concerns with the quality of water from over half (Moglia *et al.*, 2014). A study of two large tanks (185,000 and 110,000 litres respectively, about 20 – 30 times what is often considered optimum for domestic use) showed that they could have a potential payback period of about 20 years, (Imteaz *et al.*, 2011).

The variable nature of stormwater flow requires significant storage for it to be a viable option, and capturing water in a city where land is most expensive creates an inherent economic barrier. This can be overcome in some cases by installing lakes which increase the value of surrounding properties, or the use of managed aquifer recharge (MAR) where possible. Treatment trains for stormwater including swales, buffers, wetlands and bio-retention basins are capable of consistently producing high quality water and the cost of treating this to potable standards is lower than treating sewage.

An alternative supply network (known as a third pipe schemes) have been installed in a number of regions in Victoria, Australia (e.g. Barwon Water, Yarra Valley Water, South East Water and City West Water). Potable supply is still required, so water substitution becomes an additional rather than replacement cost. The only saving is the variable water cost which tends to be a smaller component of the overall charge (Essential Services Commission, 2015). The land required to provide adequate storage, and the associated cost, is likely to limit wide scale implementation within city boundaries (Hamlyn-Harris *et al.*, 2015). McArdle

et al. (2011) completed an analysis of centralised capture and use of stormwater in Newcastle, NSW, Australia. They calculated that while the cost was high at that time, it may become cost effective. However, the storage was within the city limits and the discussion of environmental impact was limited to the loss of habitat due to the construction of a dam. Dillon et al. (2014), as part of the Managed Aquifer Recharge and Stormwater Use Options (MARSUO) project in Adelaide, demonstrated that reusing stormwater in public open spaces was the cheapest option for an alternative water supply. Treating and using stormwater as a drinking supply was the next cheapest option, significantly cheaper than desalination in this case where Managed Aquifer Recharge is possible.

The cost of recycling sewage is significantly lower than seawater desalination and comparable to the current cost of surface water (Côté *et al.*, 2005; Moran, 2008). Distribution costs for this are high if the water is to be used as fit-for-purpose non-potable supply, similarly to stormwater, although as the supply is more regular, the storage requirements are much lower. Additional distribution costs can be eliminated by the use of recycled water as part of the potable supply, however, this does bring the associated issues of community acceptance and long-term health.

2.6 Modelling

Stormwater models cover many aspects including runoff from variable land use, quantity and quality of stormwater, and flowrate of water through gutters and pipes. In the urban environment they can be separated into two basic categories, hydrologic and hydraulic models. Hydrologic models are primarily interested in the amount of water available. They consider rainfall, the imperviousness of the surface, expected evapotranspiration and infiltration, and therefore the amount of stormwater in excess. Hydraulic models consider the rate of flow, water depth and the size of the different conveyances required to manage the amount of water to be handled.

Models also vary widely in structure. Conceptual models attempt to understand the physical mechanisms within a system and may range from purely qualitative to quantitative. Alternatively, an empirical model is a quantitative model based on observed data but may not have strong conceptual underpinnings. Spatial characteristics can be handled differently with lumped models assuming that the conditions are the same across a given area while a distributed model allows variation. Data processing within models can also differentiate, with deterministic models generating the same results each time given the same inputs, whereas stochastic models can produce variability based on the probability of events occurring.

Singh and Woolhiser (2002) identified over 70 hydrologic and hydraulic models available at the time. Many of these have been developed for a specific purpose or condition. A similar study (Zoppou, 2001) recognised that there ‘were literally hundreds of models’, although 12 were chosen as being representative of many of the modelling aspects. Modelling specifically for WSUD has been developed with Elliot and Trowsdale (2007) identifying 40 models that included these elements.

As IUWM developed in practice and computing power developed concurrently, integrated water modelling also advanced. However, the use of ‘integrated’ to describe models with varying parts, and the management of the total water cycle can lead to confusion. Bach et al. (2014) identified a range of stormwater models for various aspects of the management process that were all ‘integrated’. They devised a nomenclature that differentiated the objective of these models (Table 2.4). This is helpful when considering what type of model to be used, but is not of widespread enough use for models to be generally described in these terms.

Table 2.4 – Degree of integration of different model types

Model Type	Degree of Integration
Integrated Component Based Models	Integrated within the sub-system e.g.: treatment plant
Integrated Urban Drainage Models	Integrated within the urban drainage system
Integrated Water Supply Models	Integrated within the supply stream
Integrated Urban Water Cycle Models	Integrated across streams but within the urban water cycle
Integrated Urban Water System Models	Integrated across other infrastructures

2.7 Review Summary

IUWM has many aspects that have been well documented and have been or are the focus of significant research. These include but are not limited to:

- Increasing water stress and the requirement for additional water supplies
- The link between higher directly connected imperviousness and an increase in peak downstream flows

- Modifying catchments to slow flow and protect streams
- Improved stormwater treatment trains to lower pollution levels
- Reducing heat island effects and slowing stormwater flow through use of green buildings
- Wastewater recycling and re-use
- Overcoming institutional barriers to implementation of IUWM

Environmental damage caused by excess stormwater flow from impervious areas has resulted in the development of improved stormwater management which has delivered significant benefits. Water Sensitive Urban Design is well practised in many countries, although the title may vary, particularly the United States, United Kingdom and Australia.

There is a widespread recognition that the urban water cycle must be managed more comprehensively, rather than as individual components, and this broad approach is described as IUWM. However, there are issues with the implementation of IUWM including economics, social acceptability and institutional resistance, and these have been a significant area for research focus.

Within the framework of IUWM and alternative water supplies, desalination provides the greatest volume of potable water, with the rate of sewage recycling to supplement supplies also increasing. The use of stormwater to supplement supplies is lower, and has occurred predominantly in areas where Managed Aquifer Recharge is available.

2.8 Research Gaps

In temperate climates the stormwater runoff from a city, in excess of the runoff from a natural catchments, has been estimated to be adequate to meet the entire demand of that city (Charalambous *et al.*, 2012; Garrison, 2014; NRDC, 2014; PMSEIC, 2007). While stormwater use does occur in places with Managed Aquifer Recharge available, this idea of a Water Sensitive City with an effectively 'closed-loop' water cycle in a city with a temperate climate without aquifer storage has been discussed conceptually but not significantly practiced.

This scenario of a temperate climate, limited aquifer storage and increasing demand on current water supplies, describes the situation in south-eastern Australia. Irregular rainfall patterns and low natural storage has resulted in Australia generally requiring a high ratio of storage reservoirs to usage compared with other parts of the world. The Millennium Drought from 1997 – 2010 placed significant pressure on water supplies and encouraged alternative use. However, despite the apparent necessary conditions and significant research, the use of stormwater to supplement supply is low.

It is therefore of interest to further investigate the merits of stormwater as an alternative supply and why it does not occur more frequently. The primary condition for providing additional stormwater as a resource is the increasing imperviousness of the potential city catchment and the assumption is regularly made in urban water balances that these are proportional. As the increase in impervious surfaces has been occurring over a long period during which time there is river flow data it should be possible to both test the assumption that this will provide additional water, and quantify the water that may be available. If IUWM is to be successfully implemented, this must be rigorously established. While there is some understanding of the impacts of urbanisation on streamflow, a detailed method for assessing the relative size of these impacts over time has not been identified previously.

It is often assumed in models of development such as the Urban Water Transition Framework that progress follows regular stages. While this framework has been used to assess progress at a particular time in previous studies, there has been no identified study of the long term development of a city compared to this theoretical framework.

Water consumption and drivers of water use are an inherent requirement in an assessment of the urban water balance, however, the analysis of water use often relies on short term, localised studies. Long term community wide studies are possible but it often proves difficult to assess detailed water use.

Urbanisation affects infiltration and can therefore impact groundwater levels. This relationship is often not considered when undertaking an urban water balance.

When deciding on alternative pathways for addressing complex problems such as IUWM, a comparative analysis is required. Techniques such as Multi-Criteria Decision Matrices often simplify these to a single number result, removing the complexity and uncertainty of the analysis.

A study of a city, such as Ballarat, that has been growing over significant period, and for which water consumption and streamflow data is available over a substantial period provides the opportunity to investigate the potential for establishing stormwater as an alternative water supply given all the complexities of urbanisation. The potential impact on the flow regime, as an indicator of environmental condition, can also be established. The impact of urbanisation on groundwater and its influence on streamflow will also be considered. From this, as improved understanding of the requirements for establishing widespread alternative water supplies can be gained.

2.9 Research Questions

Based on the research gaps identified, five research questions become apparent:

1. Does the long-term development of water management within a city provide insight into what drives decisions, therefore informing future progress?
2. Can the drivers of water use be adequately determined from a community wide, historical analysis such that future regulatory decisions can be informed?
3. Will assessment of the long-term streamflow of a river, combined with an urban water balance of the catchment, enable the identification of additional stormwater flow due to urbanisation, in excess of the natural flow?
4. Can the impact of urbanisation on groundwater be identified (i.e. trends quantified or qualified) from the city's legacy data or any available data sources, or models?
5. Is it possible to establish a comparative analysis technique that accounts for the uncertainty of information which changes over time, maintains intellectual rigour and is understandable and easily presented?

Answering these questions will test the paradigm that increased stormwater runoff from expanding impervious areas could be captured and used to supplement a city's water supply, while mitigating the environmental impact this runoff causes.

3. METHODS

Many of the chapter presented in this thesis have been published or submitted for peer review to journals and so have standalone descriptions of methods used. The purpose of this chapter therefore is to provide a focus on the broader structure of the research and includes sections on:

- The appropriateness of a case study
- The choice of a case study city
- The use of secondary data for research
- Modelling within the analysis
- Boundaries of the research

3.1 The appropriateness of a case study

Case study research has been described as valuable as it enables phenomena to be investigated in a real life context, typically using multiple sources of data (Rowley, 2002; Yin, 2017). As by definition a small sample size is used, the study must be done appropriately, and care must be taken to generalise and generate a theorem.

The framework for understanding the urban water cycle and IUWM has been established over the past thirty years (Angelakis & Xiao, 2015; Barton & Argue, 2009; Bell, 2015; Sharma *et al.*, 2008; Wong & Brown, 2009). A case study is therefore an appropriate method to test one aspect of this model, the additional surface water generated from increased imperviousness, which can then be utilised to enhance supply. Investigating this in a real-world context is an objective of this work. A case study used in this way can be particularly illustrative of the issues and challenges of IUWM and provide supporting evidence for improvement and may it confirms pre-established theories.

Elements of historical research analysis are also used throughout this thesis, as observations and information over time are recorded and compared to a theoretical construction (Cook, 2015). As variables are not controlled, it may not be possible to assign causation, however, whenever strong correlations are observed these can be compared to other situations and areas of likelihood or further investigation identified.

3.2 The choice of a case study city

A case study city for this research should demonstrate the contemporary issues facing urban water and the development of IUWM. These include population growth, increasing urban density, limited water supply from traditional surface and groundwater catchments, environmental issues from disposal of waste water and stormwater and the impact of climate change. For an effective study there must be adequate data availability for analysis.

Ballarat is a city in south eastern Australia (37.5622° S, 143.8503° E) of 103,964 inhabitants in 2016 (Australian Bureau of Statistics, 2017), approximately 110 km west of Melbourne (see shown in Figure 3.1), the state capital of Victoria. The area around Ballarat was historically a forested catchment sparsely inhabited by Indigenous (Wadawurrung) people. The first European pastoral settlement was in 1837 with a small community following in 1841, but the population exploded soon after when gold was discovered in 1851 (Victorian Government, 1857). The location was thus determined not by geography or water availability as is the case with many cities, but by the gold discovery. This is a feature shared with other resource-based cities, however, it does not necessarily ensure an optimal water supply. Ballarat is located at a relatively high elevation, and covers the upper reaches of five catchment basins (Figure 3.1). The domestic and industrial areas are predominantly within Yarrowee and Leigh River catchments (Barwon Basin) which also receives the majority of stormwater from the city.

Initial water supply was established in 1856 within the upper reaches of the Barwon Basin. Within ten years this proved inadequate and the first reservoir was constructed in the adjoining Moorabool catchment (or watershed). It is facing many of the typical water issues confronting communities throughout the world. It has grown from 50,930 people in 1957, and is forecast to continue growing to 140,000 people in 2030 (profile id, 2015). Existing surface water supplies are limited and there is a reliance on inter-basin transfers for supply (CHW, 2016). Water is predominantly sourced from the Moorabool River in the adjacent basin, but the security of water supply also relies on transfers from the Campaspe River in northern Victoria via the Loddon Basin. Groundwater has been used to supplement supply in times of extreme drought. Harvesting stormwater using Managed Aquifer Recharge has been trialled (CHW, 2016), rainwater tanks are standard in new homes, and other WSUD features such as buffer strips, swales, bio-retention swales, ponds and lakes, and constructed wetlands have been installed in some housing developments.

Ballarat is in a temperate climate zone, with average rainfall (1908 – 2016) of 689.9mm close to the city centre, but higher falls, 848.5mm, (1882 – 2016) within the water catchments (BOM, n.d.). The average maximum temperature in the hottest month (February) is 25.2°C, while during the coldest month (July) this drops to 10.1°C, and the average minimum

temperatures for these months are 10.9°C and 3.2°C respectively. There is an occasional sprinkling of snow which rarely settles and has no different effect on the water balance than rain.

From records obtained via the local urban water utility (www.chw.net.au), the sewerage network commenced in 1922, and the initial treatment plant, Ballarat South, discharges to the Yarrowee River, and currently processes about 66% of Ballarat's wastewater. The 'Ballarat North' treatment plant has processed the remaining 33% of wastewater since being established in 1972 and discharges into the Hopkins River Basin. In addition, mine de-watering from Ballarat Goldfields is transferred into the Yarrowee River. Groundwater, sourced from upper aquifers outside the Yarrowee River catchment, was used to supplement supply during the Millennium Drought (1997 – 2008).

A number of monitoring stations (river gauges) have been established on the Yarrowee River, however, the current one on the Leigh River at Mt Mercer (233215) has been operating continuously in its present form since 1956 (DELWP, n.d.-d). This is approximately 29 km south of Ballarat, with a total contributing catchment area of 593 km². While a river measurement point closer to the city would be more sensitive to the effect of urbanisation, none is available. However, measurements from this gauging station demonstrate the overall impact on the catchment due to growth and spread of the city. Rapid clearing of the native vegetation occurred during the second half of the 19th century, associated with gold rush era. Since then significant peri-urban development in the form of hobby farms and lifestyle properties occurs throughout the catchment. Farms, forests and timber plantations comprise the majority of the remaining land uses. There is no irrigated farming and the licensed extractions from the river are for relatively small volumes of stock and domestic water uses.

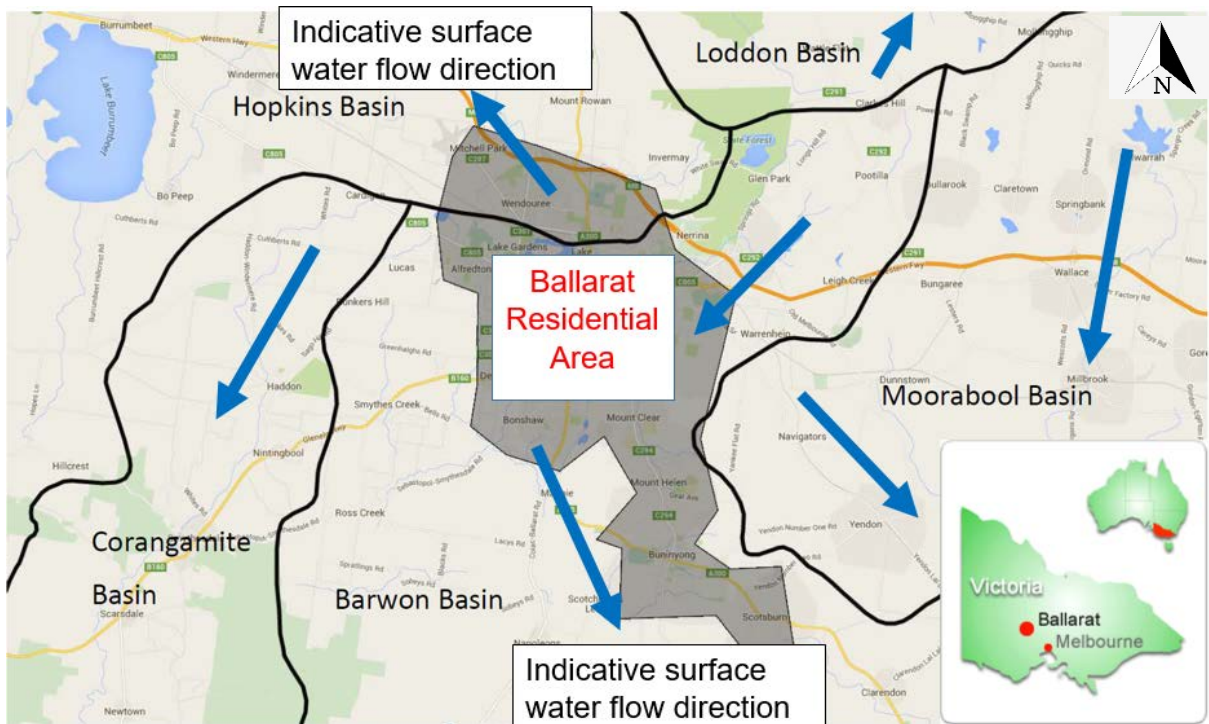


Figure 3.1- Ballarat and surrounding catchment basins.

As an inland city, there is potential for stormwater capture downstream of the city. As increased urbanisation is expected to result in higher stormwater flows, it may be possible to harvest some of the stormwater flows while maintaining pre-development flows in the receiving waterway. ‘*Harnessing Ballarat’s Stormwater Project*’ (Rossiter, 2013) identified stormwater detention basins which could be used as temporary storages to then supply public open spaces. While there is now some stormwater use for filling recreational lakes and watering public open space, the overall percentage of use is low.

Climate predictions (Ricketts & Hennessey, 2008; CSIRO, 2015) suggest that there will be a temperature and rainfall changes over the next twenty years. The predictions vary dependent on the scenario assumed, but under all predictions a temperature rise of 0.4 – 1.1°C is expected by 2030. Overall rainfall depth may not alter significantly in this time frame, although temporal patterns are expected to change including more dry periods.

As a city with increasing demand, experiencing climate and population change, requiring water from outside its catchment, and the potential for MAR and centralised above ground storage, in addition to a substantial history of water development and historical data, Ballarat displays the features of IUWM and stormwater use and an opportunity to test the implicit assumptions within the IUWM framework.

The case study approach has been used to good effect in other studies of urban water. SWITCH, a major research partnership funded by the European Commission between 2006

and 2011, developed a City Water Balance and completed case studies in Birmingham, UK and Dunedin, Florida, USA (Mackay & Last, 2010). A similar approach to the urban water balance was undertaken in Cyprus, Greece (Charalambous *et al.*, 2012) and comparisons of important aspects considered in cities of Australia (Kenway *et al.*, 2011). Examples of case studies highlighting residential use in south-east Queensland (Beal & Stewart, 2011), Integrated Water Management planning in Melbourne (Wilson *et al.*, 2013) and the environmental history of Perth (Morgan, 2011) also demonstrate that use of Australian case studies can highlight universal themes.

This case study includes a number of unique features, which will inform the development of IUWM. It uses a long-term historical approach to provide perspective on more recent changes to water management. New techniques are developed to understand the drivers of water use. It links the city water balance with hydrologic modelling and includes groundwater and surface water interactions to get a complete picture of the urban water cycle.

3.3 Scalability and transferability

Undertaking a case study is of limited value if knowledge cannot be transferred to other places. The majority of development throughout the world is taking place in cities much larger than Ballarat. In Australia, more than 60% of people live in five cities, all greater than 1.3 million people (Australian Bureau of Statistics, 2017), while the rise of mega cities throughout the world continues. The ability to scale results must therefore be considered.

The consideration of the impact on a city as a whole on an annual basis is important, irrespective of the size. This is possible for Ballarat where in larger cities the data may not be so readily accessible as there is less likely to be a convenient single downstream river, closed catchment or alternatively, water use data segmented by sub-catchments with agencies having different responsibilities for components of the water cycle across catchment boundaries.

The complexity of urban hydrology is an issue, whatever the size of the city, and impacts on groundwater will vary based on the geomorphology and types of development. The need to consider these issues when assessing potential stormwater availability is universal and care must always be taken if trying to scale findings directly. While directly scaling results from case studies can be problematic, the methods used in this thesis allow for replicability to other comparable cities, growing regions and suburbs with emerging IUWM needs.

3.4 Using secondary data

The sources of data for the historical information and the methods of analysis used for each of the results sections are discussed fully in those papers and can be found in the relevant chapters. This discussion is focussed on the widespread availability of existing data and the issues and potential with using this for research, particularly within the area of water management.

We live in an age when more data is available than ever before (Mayer-Schonberger & Cukier, 2013; Schmidt & Cohen, 2013). The increase in digital data generation and storage has led to opportunities of big data and data mining to exploit this and gain understanding that may not be identifiable from smaller data sets. This is possible for data that has been digitised, but there has also been historical data collected which is available. The water industry has been collecting data on supply and demand since its establishment, some of which is available in digital form, while older data has been kept in original documents in archives and libraries.

One of the possibilities with secondary data is to enable analysis which was not intended when the data was first collected (Berman, 2015). While this is true, it can be problematic in that the form of the collected data varies over time as the purpose for collection changes.

Data sources for the water industry in Australia include

- Annual reports from water authorities. These include water supply and storage, water use, sources of water and price of water. While more recent years are available on line, as semi-government institutions they have been thorough in maintaining historical copies and annual reports are available since the organisations commenced (CHW, 2016; Melbourne Water, 2017b; MMBW, 1934).
- Bureau of Meteorology climate records. Rainfall and temperature data is available in digitised form for all weather stations which have collected data since the Bureau commenced (BOM, n.d.).
- Water Management Information System (WMIS) from the Victorian Department of Environment, Land, Water and Planning (DELWP). This is an on line system with surface water and groundwater records (DELWP, n.d.-d). While the Victorian data set has been used for this work, similar records exist in other states of Australia and other countries.
- Victorian water accounts, previously the State water reports, are annual reports on water availability and resources at the catchment scale. A water balance of each

catchment within Victoria is completed, including transfers of water between catchments. This is available from some 2003. (DELWP, n.d.-b)

- Visualising Victoria's Groundwater (VVG), an on line portal developed by the Centre for e-Research and Digital Innovation (CeRDI) at Federation University, Australia, which brings together data from a range of disparate sources to provide up to date groundwater information throughout Victoria (CeRDI, n.d.).
- Australian Bureau of Statistics (ABS) collects community information on a range of subjects including population, and the water account (Australian Bureau of Statistics, 2013b, 2017).
- Catchment management authorities are responsible for the integrated planning and coordination of land, water and biodiversity management (DELWP, n.d.-a).
- Rural water authorities license extractions from groundwater, rivers and large dams and manage irrigation areas throughout the State of Victoria (Southern Rural Water, n.d.-b).

The use of legacy data is appropriate when attempting to assess what has occurred based on previous changes, as is the case with this thesis. Data that has been collected for climate monitoring, water resource management and urban development can be analysed to determine impacts of urbanisation on the water cycle, and assess whether the expected outcomes predicted by IUWM have occurred. The use of data already collected for other purposes does mean that analysis can be completed relatively quickly (Berman, 2015).

The use of legacy data, particularly when collected at a community-wide scale, does mean that variables are not controlled as would be the case in many scientific experiments which depend upon fixing as many variables as possible, making managed changes and observing the reaction of dependent variables. However, this may be overcome if the data sets are large enough that significant trends can still be determined, other influences can be accounted for or the effects are expected to be larger than those caused by other variables. It also reflects reality. Changes to water management must occur within the context of social, political, technological and climatic changes, and if an opportunity is significant enough to exploit, while it may not be possible to definitively determine causation, significant insights can still be identified. Comparisons with other studies, predicted results and expectations from a variety of observations can provide enough validity to warrant further consideration.

The use of community wide data eliminates one criticism of controlled water use studies in the home which must practically use a relatively small sample size that may not be reflective of the population. Self-selection of interested candidates, the observer effect, and isolation

of changes made from other community influences all raise concerns as to whether findings can be universally applied. Use of whole population data ensures that any stated effects are large enough to be distinguished from the inherent noise. The use of total system data, even though there are many uncontrolled variables, can also overcome a criticism of reductionism where testing of single factors in isolation can be seen to not represent what is occurring in the 'real world'.

While there are difficulties in obtaining data and ensuring it is in similar format for analysis. The relative availability and large quantity of information available when compared with primary data collection creates an opportunity for new understanding to be gained efficiently.

3.5 Modelling

There are three components of modelling within this thesis, all of which inform the analysis within Chapter 6. These are a city-scale annual water balance, rainfall-runoff hydrologic modelling, and the impact of farm dams.

3.5.1 Water Balance

The city-scale water balance has been completed at an annual time-step over a sixty year period. This concentrates on water supply and measured water flows, using these to calculate the component of river flow attributable to rainfall on the catchment. There is no hydrologic modelling in this analysis. The greatest complexity within the water balance is the collation and sorting of information over a long time period in a common format, thus enabling relatively simple analysis to provide the required results. The data required include:

- Precipitation on the city and catchment;
- Bulk transfers of water in/out of the city;
- Water consumption within the city;
- Treated wastewater volumes to receiving waterways;
- Abstractions from waterways; and
- Streamflow data for the receiving waterway.

This data is available in various forms, however, all of it can be obtained on an annual basis which removes seasonal effects while still providing adequate decadal water balance analysis. Seasonal variations, peak flow magnitude and frequency analysis, and rate of change are all important determinants of urbanisation impact and IUWM and can be

measured using a different time scales, which are important for assessing ecological impact. However, when assessing the total water resource, particularly in the context of volumes available to supplement supply, an annual time frame with sufficient data to detect trends is appropriate. For a water balance of this nature, annual data over 60 years with nine variables, a spreadsheet model is capable of handling these calculations adequately.

The water balance methodology is described in more detail in Chapter 6.

3.5.2 Rainfall-runoff hydrologic modelling

To understand the changes in the rainfall/runoff relationship due to climate rather than catchment alterations hydrologic modelling is required. The Australian Water Resources Assessment Modelling System (AWRAMS) is a grid based, integrated hydrologic model developed by the Australian Bureau of Meteorology (BOM) and Commonwealth Scientific and Industrial Research Organisation (CSIRO) (Elmahdi *et al.*; Frost *et al.*, 2015; Hafeez *et al.*, 2015; Viney *et al.*, 2015). It can provide evapotranspiration, soil moisture at depths to six metres and runoff since 1911 in Australia based on unimpaired catchments. It has been calibrated and validated using 595 river basins with common parameters used for the model in all areas. While this broad scope gives strength in the amount of data available and robustness, it can mean local calibration issues are not considered, however published calibration results indicate performance is similar to locally calibrated models (Frost *et al.*, 2015).

Data was provided by the BOM for the Barwon River basin for daily, monthly and yearly intervals from 1911 until 2016, and is the strongest and most robust modelling available, although it was not targeted for this particular catchment or purpose

3.5.3 Impact of farm dams

Surrounding the city is a peri-urban fringe where larger allotments are purchased for lifestyle residences, often with a dam for watering animals, garden or aesthetics. The number of farm dams in the catchment has been calculated using visual counts from aerial photographs (Victorian Government, n.d.-a), Google Earth, and current data confirmed using the Victorian Water Asset Database (DELWP, n.d.-c). STEDI (Spatial Tool for Estimating Dam Impacts) is modelling software that calculates the impact on runoff due to dams (Nathan & Lowe, 2012), completing a water balance around each dam, each time step, accounting for inflow, rainfall, evaporation, removals and bypass. The model can predict the impact of future dams or

effect of previously installed dams. The detailed methodology of how the STEDI software is used and how this contributes to the analysis is given in Chapter 6.

While modelling is a necessary part of this research, the combination of a range of information from a variety of sources and the time frame which the analysis considers provides the greatest value, rather than any difference which may be obtained by varying the detailed modelling approach.

3.6 Boundaries of analysis

3.6.1 Place and time

Historical case studies have inherent limitations in they are specific to a particular place and time. While they provide the ability to explore a situation in detail and are grounded in reality, which can then lead to new theoretical developments, they are by definition unique, and not necessarily able to be generalised (Hodkinson & Hodkinson, 2001). Ballarat is an exemplar city facing similar contemporary water management issues to many cities throughout the world. Many insights can be found using case studies, although care must still be taken in extrapolating results. Throughout this work, case study results have not been presented as representative of the reality for other cities, but rather as indicators of where the similar results to other places have been confirmed, or surprising results which question or challenge our understandings of the underlying assumptions.

While the philosophy of IUWM is universal, in that use of waste streams and fit for purpose water use provide opportunities for resource management and an improved lived environment, the implementation is highly dependent on local conditions. Australia is seen as being at the forefront of IUWM (Wong & Brown, 2009), necessitated by the variable rainfall and lack of natural storage as ice and snow. However, across Australia the ability and desire to use stormwater to supplement supply for example, is quite different. In the City of Perth, the sandy soils and reduced rainfall over the past 40 years has resulted in less than 10% of previous surface water supplies being captured (Water Corporation, 2013), however it also means there is no surface stormwater runoff. Stormwater from roofing is discharged locally into the soil where it drains into the aquifer where it is be recovered for re-use as a major part of the water supply.

The City of Adelaide, with the lowest average rainfall of all Australian capital cities, has implemented a trial Managed Aquifer Recharge scheme for the capture of stormwater, primarily for the watering of gardens and public open space. In Melbourne, with no aquifer readily available, while WSUD techniques are utilised for stormwater management and some third pipe schemes implemented at development scale, the use of stormwater is low overall.

This demonstrates that even within one country that is universally facing the need for additional water supplies, differences in climate and geology result in a range of responses.

These differences are more pronounced when considering different countries and climates, even within the same region. The distance between New Zealand and Melbourne is similar to that from Melbourne to Perth, but there the water issues revolve around how to cope with excess flows. This is similar to the different issues faced between high river flows in the eastern United States, compared with California in the west (Naiman, 2014; United States EPA, 2000).

However, difference in conditions between cities are inherent, and this does not mean that lessons and principles cannot be applied within common issues being experienced even in cities with disparate climates. Therefore, while the limitations of a case study must be acknowledged, they can provide an opportunity to either confirm expected results in a different situation, or provide reasons and techniques for testing assumptions.

3.6.2 Utilising annual stream flow

IUWM is a systems framework, considering all aspects of the water cycle and the interplay between these. Its benefits include improved urban amenity and reduced environmental damage. One aspect of IUWM is the recognition that stormwater can be utilised as an additional water resource. This commonly occurs in a distributed manner with the use of rainwater tanks, and swales and buffer strips being automatically watered. Within communities it may extend to wetlands and a 'third pipe' distribution scheme. While much of the development work within IUWM has concentrated on solutions at a short time scale over which the peak flows have much of their impact and there is additional water availability, the current research has focussed on the annual water balance and associated water availability. It therefore complements many of the founding issues around which IUWM was developed.

Magnitude of peak flows, frequency of flow peaks, rates of change of flow, time periods of and between flow events, and no flow events, are all acknowledged issues for streams downstream of urban environments. These issues have not been specifically analysed for this thesis, although they have been considered in discussions throughout. While these issues are significant, and as discussed within the literature review, there is a large and growing body of evidence on how to address these problems effectively. The purpose of this work is to analyse one part of the IUWM framework being the potential for stormwater use to significantly impact the water supply of a city. To enable this, aspects of the urban water balance, other than just surface runoff, needed to be considered over a longer time-frame. While seasonal, temporal and geographical changes are of great importance, the longer-term

view of the overall water balance was also required to determine whether additional water resources are potentially available.

The analysis undertaken also inevitably reflected the data which was available. While streamflow data is available at hourly time intervals or less, and rainfall data at daily time steps, transfers between catchments, consumption and sewage plant data is only available in relatively coarse time steps for the sixty-year period of analysis completed in Chapter 6. Therefore, while there is a recognition that short time frames are important for different aspects of flow regime analysis, for the water balance to measure the overall ability for stormwater to significantly supplement the water supply of a city, an annual time step was deemed more suited for this regional scale problem.

4. BALLARAT'S MESSY PATH TO A WATER SENSITIVE CITY: a long term investigation into water management of a city

To assess the potential for stormwater to substitute a significant quantity of the existing potable water supply an assessment of the potential requirements for a city must be made. Historical use data will inform the predictions of future use.

A Water Sensitive City describes the potential future state where IUWM is fully implemented and a component of a sustainable city. Understanding the path from the establishment of a city and its water supply through multiple changes in water management provide information regarding what drives decisions about supply and demand.

This chapter describes the history of Ballarat water management from the establishment of the Ballarat Water Board in 1880, and compares development within the city to the Urban Water Management Transitions Framework used for assessing progress toward the goal of a Water Sensitive City. Initial results from this work were presented as a peer-reviewed conference paper at the Hydrology and Water resources Symposium, Queenstown, New Zealand in December 2016 (Ebbs *et al.*, 2016). The chapter as presented was published in Water e-Journal, the Australian Water Association online hub for water, science and (peer-reviewed) technical paper publication in Australia (Ebbs *et al.*, 2017).

Ebbs, D., Dahlhaus, P., & Kandra, H. (2016). *The journey to a Water Sensitive City - A case study of Ballarat, Victoria, Australia*. Paper presented at the Water Infrastructure & the Environment, 56th New Zealand Hydrological Society, 37th Australian Hydrology and Water Resources Symposium and 7th IPENZ Rivers Group, Queenstown, New Zealand, Nov 28 - Dec 2, 2016.

Ebbs, D., Dahlhaus, P., & Kandra, H. (2017). Ballarat's messy path to a water sensitive city; A long term investigation of water management in a city. *e-water; The journal of the Australian Water Association*, 2(4). Retrieved from http://www.awa.asn.au/AWA_MBRR/Publications/Water_e-Journal/Vol_2_No_4_Ebbs_Water_Sensitive_Cities.aspx

4.1 Abstract

Water security is a vital part of ensuring a sustainable future. This is particularly true for many cities in Australia where relatively low rainfall, population growth and climate change places communities under water stress. The 'Water Sensitive City' is one in which water is drawn from a range of water supplies and that sustainably interacts with its surrounding environment. Every city has a unique water history in which the economic, environmental and social history have impacted on the development of water management. Tracking the evolution of water management of a city and its deviation from a standard pathway can provide information regarding what drives decisions about supply and demand.

Water management in Ballarat has been tracked from the establishment of the first water supply to the city in the 1850's until 2015 using historical records from the local water authority. These records show some key differences between Ballarat's water management history and the Urban Water Management Transitions Framework. This highlights that decisions are a function of the individual situation and circumstances in which a city resides. In particular, the water demand declined from a peak in 1980, well before climatic conditions and severe water restrictions were implemented. Understanding the social, environmental and economic drivers of this reduction in demand may assist in future urban water management decisions. When alternatives are considered, if factors other than economics are considered important, these must be included in the comparative analysis.

Key Words: Water Supply, water demand, urban water, Water Sensitive City, water management, history of water management

4.2 Introduction

The term ‘Water Sensitive City’ has entered the lexicon of urban water management. It was introduced as the final stage in the Urban Water Management Transitions Framework (Brown *et al.*, 2009), and describes a city where a diverse range of water sources is utilised as part of a sustainable environment. The transitional stages leading to a Water Sensitive City are shown in Figure 4.1. Interest in Water Sensitive Cities is being driven by higher demand on limited water supplies, which is increasing cities water stress and placing water security at risk.

The demand for water has increased dramatically during the 20th century. Worldwide domestic water use increased 6-fold, compared to a 3-fold increase in population (Cosgrove & Rijsberman, 2000), with the introduction of hot water availability, flushing toilets, showers, washing machines and garden watering all contributing to this increase in demand as did a reduction in the average number of people per dwelling (Cheruseril & Arrowsmith, 2007; Worthington & Hoffman, 2006).

Climate change is expected to further impact water supply in many areas. Under a climate change scenario, rainfall intensity is expected to increase, with rainfall frequency expected to decrease in some regions (Intergovernmental Panel on Climate Change, 2007): increasing temperatures are predicted to lead to higher evaporation and evapo-transpiration, leading to drier soils and higher water demand by plants (Macinnis-Ng & Eamus, 2009). Further, rivers that rely on glacial and snow melt are expected to experience greater flow variability (Pederson *et al.*, 2013).

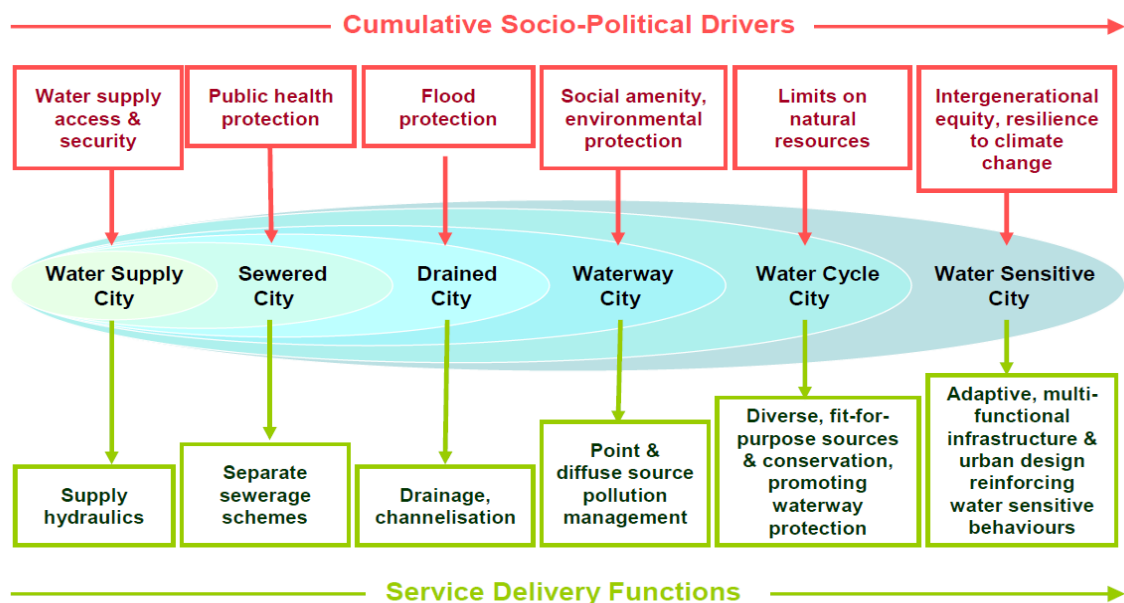


Figure 4.1- Urban Water Management Transitions Framework (source: Brown *et al.*, 2009)

The combined effects of increasing demand and climate change has been leading to increased water stress in cities with the United Nations reporting that 2.6 billion people currently lack adequate supplies of clean water and sanitation (World Health Organization, 2015). Additionally 25% of cities with a population over 750,000 are currently suffering from severe water stress (McDonald *et al.*, 2014), and 80% are rated as vulnerable (Padowski & Gorelick, 2014). The demand on groundwater, which is estimated to provide 35% of freshwater worldwide (Chu *et al.*, 2013), is forecast to exceed supply during the next century (Taylor *et al.*, 2013).

To address the problem of increasing water stress in cities, Brown *et al.* (2009) proposed an Urban Water Management Transitions Framework (see Figure 1) to assist in the transition to more sustainable city water management and, ultimately, to Water Sensitive Cities. One of the objectives was to provide a benchmarking heuristic for the assessment of a city's water management status, and although some cities may have completed this assessment at a given time, there is little literature available on the transition of individual cities over time. Every city has a unique water history in which the economic, environmental and social history have impacted on the development of water management. Analysing the path of an individual city and highlighting differences from the framework can lead to an improved understanding of what drives water management decisions.

Ballarat – a city in south-eastern Australia with a current population of 102,490 people (Australian Bureau of Statistics, 2017) – was chosen as a case study allowing the stages of water management to be identified and mapped within the Urban Water Management Transitions Framework. In the present work, we demonstrate the transitions that have taken place in Ballarat through the 20th century and highlight differences to the framework. Of particular interest is the reduction in demand from 1980, well before extended low rainfall and severe restrictions had an impact. This may highlight that the community is making decisions based on a range of social, environmental and economic factors, and understanding these could have a significant impact on the water requirements of a city.

4.3 Methods

4.3.1 Ballarat: a case study city

Ballarat was chosen as case study as many of the issues that have been identified as being important in urban water management have been recorded in the water management history of the city. It is a rural, inland city in South Eastern Australia, approximately 110 km west of the state capital of Victoria, Melbourne (see Fig 4.2).

The first pastoral settlement was established in the Ballarat area in 1837, with a small community following in 1841. The population dramatically increased following the discovery of gold in the area in 1851. The location was thus determined not by geography or water availability as is the case with many cities, but by the gold discovery. This is a feature shared with other resource based cities, however it does not necessarily ensure an optimal water supply. Ballarat is located at a relatively high point, and covers the upper reaches of four catchment basins. The majority of the city is located in the Barwon basin where initial water supply was established in 1856, and which receives the majority of waste and stormwater flow from the city. Within ten years of a water supply being established, the catchment in the upper reach of this basin was inadequate, and the first reservoir was constructed in the adjoining Moorabool catchment.

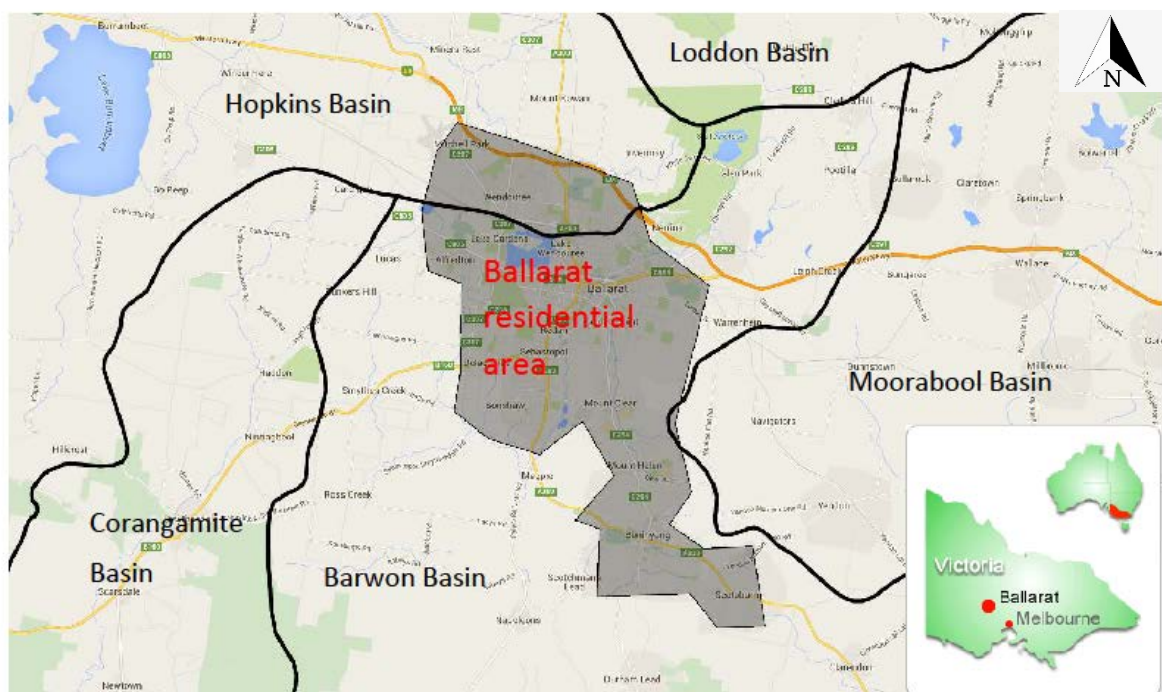


Figure 4.2 - Ballarat and surrounding catchment basins

Water stress in Ballarat is expected to increase in the future as the city's population increases by a predicted 40% in the next 20 years (profile id, 2015). Further, the city is in a temperate climate zone, and under a climate change scenario, average temperatures are predicted to increase, and rainfall is expected to decrease and become more variable (Whetton *et al.*, 2015). It is currently necessary to source water from more remote basins to maintain supply and this requirement is forecast to increase in the future (CHW, 2016).

As an inland city, there is potential for stormwater capture downstream of the city. As increased urbanization is expected to result in higher stormwater flows, it may be possible to harvest some of the stormwater flows while maintaining pre-development flows in the receiving waterway. Some housing developments featuring Water Sensitive Urban Design (WSUD) features have been constructed, and a Managed Aquifer Recharge trial completed. While there is some stormwater use for filling recreational lakes and watering public open space, the overall percentage of use is low.

4.3.2 Water use: a common understanding

The understanding about water use is clearly described in a quote from the Melbourne Water website.

“Melbourne’s water use has varied over the years, from the high consumption of the 1980’s to the water-saving efforts during the 1997-2009 drought.” (Melbourne Water, 2016)

This is consistent with Ballarat where the 2013 water plan uses 1990’s data as the baseline as it is considered representative of the pre-restriction period, with continually increasing water use. The millennium drought placed significant pressure on supply and required restrictions to match supply and demand. As restrictions and water reduction campaigns remained in place, permanent water saving methods were encouraged such as the installation of rainwater tanks, low flow shower heads and dual flush toilets. When restrictions were lifted, the water use did increase, but not to previous levels.

This commentary reflects the lived experience closely enough to have become an accepted truth. Collection of the data was expected to reveal this pattern, and become the basis for determining water requirements and the potential for savings in future work.

4.3.3 Data collection

The current urban water authority - Central Highlands Water - holds archives of the Annual Reports of water services from 1882 onwards. From these, we obtained data and information relating to the amount of water supplied, number of water connections, sewer flows, number of the sewer connections, reservoir levels, water rates, domestic and non-domestic water use and timing on the imposition of restrictions.

We note that in 1956, meters were installed to record the total amount of water supplied from the reservoirs. Prior to this, the total amount of water was recorded as the summation of all the metered supplies. A correction could have been made to allow for this change; however, the small variation did not substantially affect our results or conclusions, so the raw data has

been reported. We also note that there was no direct data available for domestic and non-domestic water use between 1956 and 1995, so rates and revenue information was used to estimate domestic and non-domestic water use during this period. The accuracy of the data met the requirements at the time, and while metering technology may have improved, data errors are not considered to be significant compared with the overall changes in water use.

In Australia, decimal currency was introduced in 1966, and all currency has been converted to Australian dollars. Similarly, imperial measures, in this case gallons for water supply, were used up until 1974, which have been converted to SI units (litres) that have been used since.

Population data was sourced from census information (Australian Bureau of Statistics, 2017; Victorian Government, 1857, 1884, 1894, 1904), which was collected at either 10-, 12-, 7- or 5-year intervals over the period. Linear extrapolation between census dates was used to determine the population in non-census years and enable calculation of water use per person. Other information affecting water management including rainfall (BOM, n.d.) and flooding (Department of Sustainability and Environment, 2015) was also collected.

From the above sources, we established a continuous data set of Ballarat water management information since 1882.

4.4 Results

The total water use in Ballarat is presented in Figure 4.3 (black line) along with water use per person (blue line) and non-domestic demand (yellow line). Five distinct phases have been identified. Each of the time periods discussed has been identified as corresponding to a transitional phase described in the Urban Water Management Transitions Framework presented by Brown et al. (2009). A low water use initial period as water supply was established (pre 1920), a gradual increase as the distribution network was extended, and drainage and sewer were established (1920 – 1940), a dramatic increase as the city became fully connected (1940 – 1980), the reduction of water use corresponding to increased environmental awareness (1980 – 2000) and further reduction due to reduced rainfall and associated restrictions (post 2000).

The building of infrastructure such as reservoirs from the 1860's, waste water treatment plants (for treating sewage) and the 'superpipe' (2008) (a diversion pipeline from a distant catchment) are also shown in Figure 4.3, as are recorded flood events.

Figure 4.4 shows the steady expansion of the Ballarat water reticulation system as indicated by the number of domestic connections (red line), The proportion of total water used which was for domestic supply (brown line), and the sewer flow as a proportion of total water

supply are also shown (green line). The water storage level (purple line) has been highlighted to identify when water restrictions were imposed and the impact of the millennium drought on Ballarat's water supplies. Despite increased storage volume, there was less water available to Ballarat in 2008 than at any other time since 1913, demonstrating the reality of water stress in a developed city in a temperate climate.

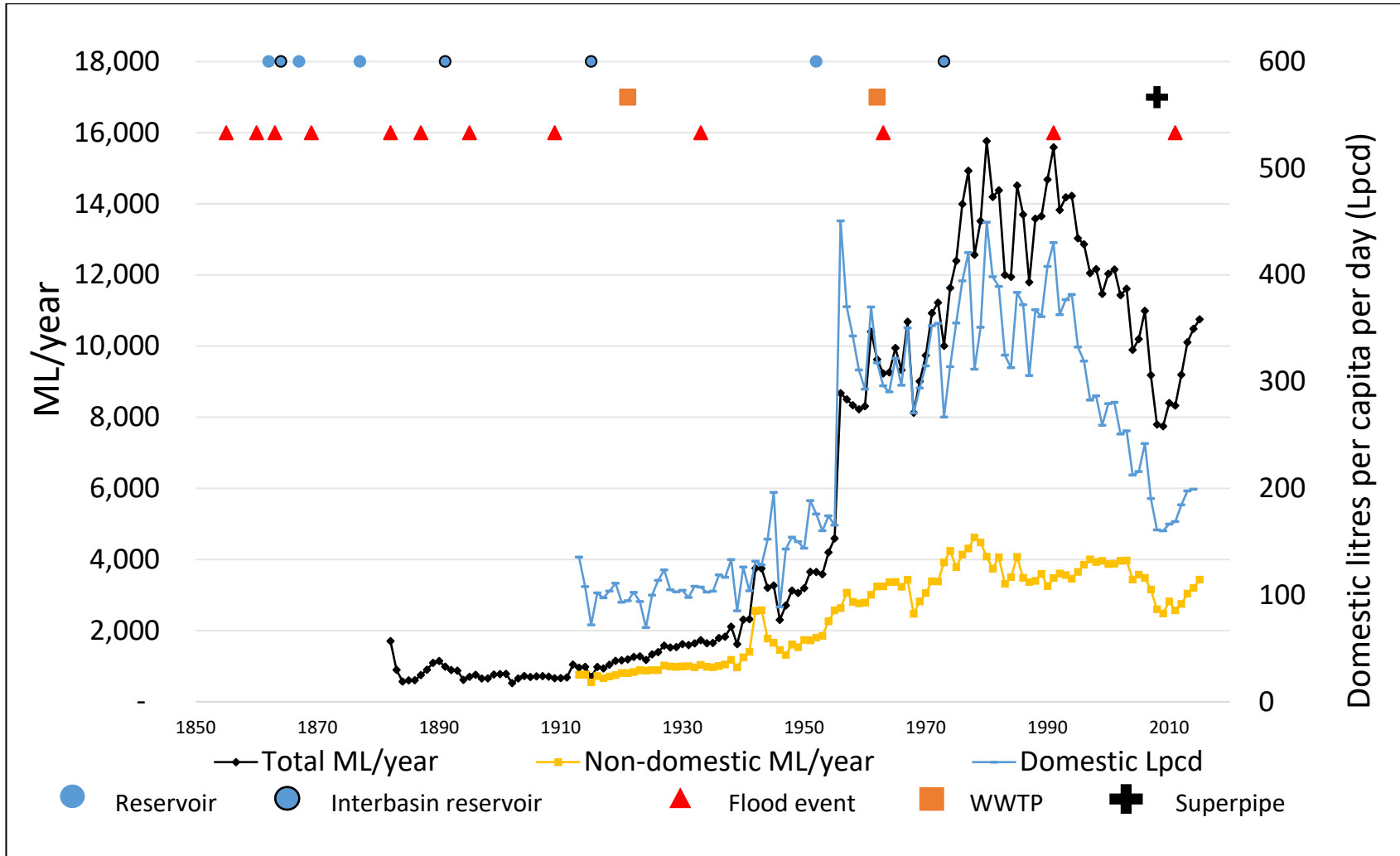


Figure 4.3 - Ballarat Water Consumption 1855–2015.

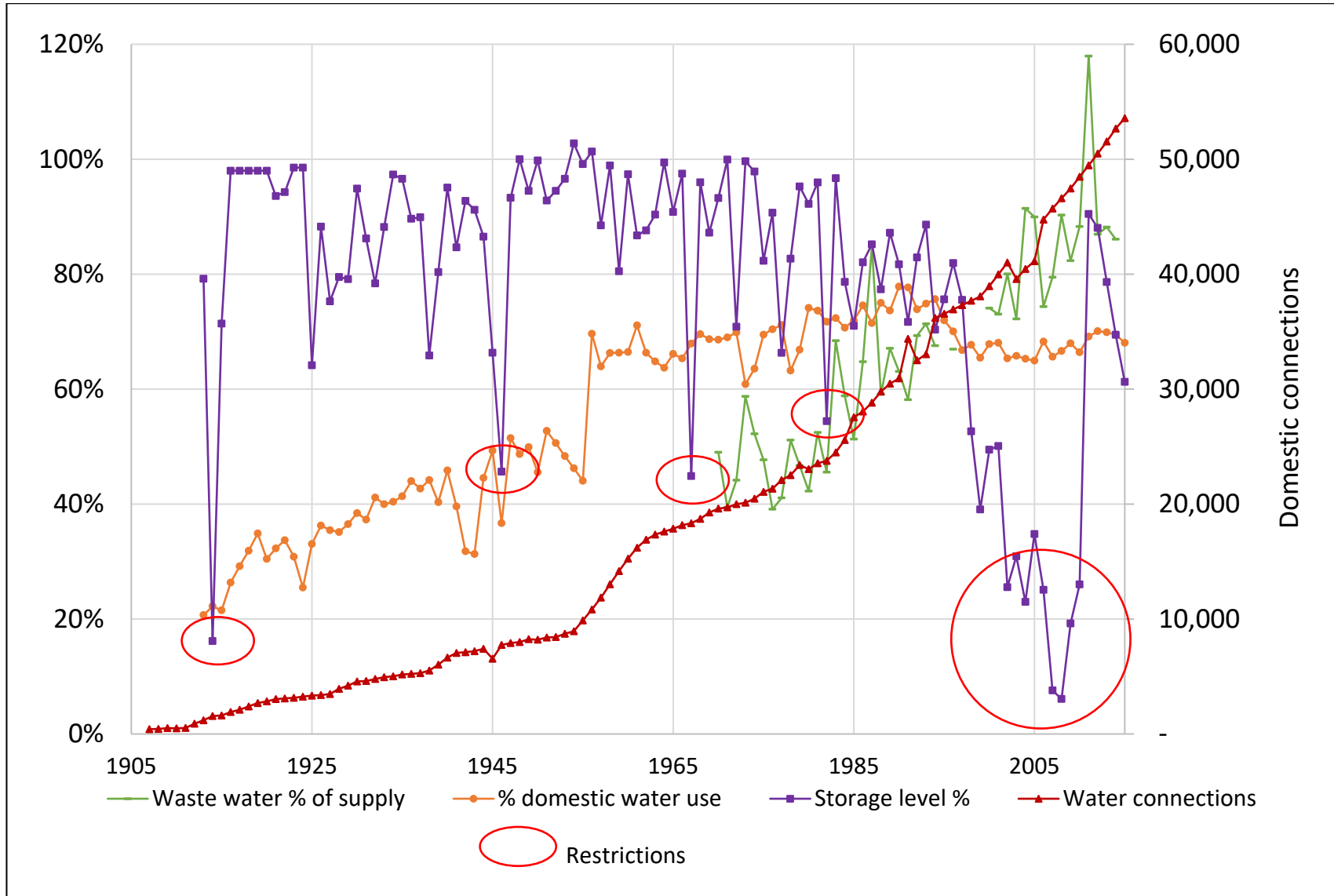


Figure 4.4 - Ballarat Water Supply and Domestic Connections 1905–2015

4.4.1 1850s–1920

Ballarat's population exploded in the gold rush of the 1850s and '60s, and reached a peak in 1868 that was not reached again until the 1970s (profile id, 2015). This led to a demand for water, domestically but particularly in the mining and associated industries. The initial supply was provided as a public standpipe, then from 1882 metered data first became available, divided into mining, manufacturing and free supply. In 1907, towards the end of the gold mining period, the first domestic connections are recorded, and metered data becomes available for domestic supply from 1913. While water use did not alter significantly during these years, enhancing the security of supply required the construction of additional reservoirs. Six reservoirs were constructed during this period; three within the Barwon basin in which most of Ballarat city is located and into which waste water drains, and three in the adjacent Moorabool basin. These were at an elevation that enables gravity supply to the city.

A lack of adequate drainage was a major issue during the mining boom. Sluice mining created very high sediment loads, choking downstream waterways which exacerbated flooding, an issue that was not resolved until 1909 (McBride, 1911). Drainage within the rapidly expanding city was also an issue, leading to the construction of the bluestone gutters and channels in the 1880's which are still in use today. Reports of flooding through historical notes and media outlets shows eight examples over 60 years. One of the most significant, the 'Great Flood of Ballarat' in 1869 (The Argus, 1869) caused the death of at least two people, and was one factor in the justification for Gong Gong reservoir, constructed in 1877 (CHW, 2016).

During this time, the establishment of a reticulated water supply but the lack of sewerage and the frequency of flood events, means that Ballarat could be described as a Water Supply City.

4.4.2 1921–1940

Metered private connections grew steadily in the period between the wars while there was little change in population. By 1940, the city's population of around 40,000 people had been relatively stable for 60 years, and Ballarat now had 6000 domestic water connections. The expansion of water reticulation and initiation of a sewerage system in 1923 had significant impacts on water management in Ballarat during this period. Total water use doubled due to the deployment of more connections, but water use per person and per connection remained unchanged.

Given the establishment of the drainage system, but an incomplete sewerage system, Ballarat during this time could best be described as existing in the second stage of the framework – a Sewered City. We note that Ballarat’s water management status deviates from the theoretical framework, which suggests sewerage implementation tends to precede drainage.

4.4.3 1941–1980

A dramatic increase in demand occurs between 1941 and 1980 during a time of population growth and increased standards of living as expected. During this period, Ballarat experienced a 6- to 7-fold increase in total water use, and per capita water use tripled. The growth in post-war Australia (the baby-boom and migration) (Australian Bureau of Statistics, 2017) is reflected in the growth of the Ballarat population. Availability of water was increased due to provision of additional reservoirs, and complete reticulation and universal connections to the sewer were provided. These changes, combined with changes in technology, resulted in increased water consumption.

In addition, two significant events that had a temporary effect on the water use occurred during this time. First, in 1940 a number of military camps were established in Ballarat. The water use within these camps peaked in 1942, when they made up approximately 10% of the total metered water supply of the city. Second, in 1956 the Olympic rowing events were held at Lake Wendouree in Ballarat, and during this year the water required for the lake increased substantially. Further, there were 2 years in which water restrictions were imposed due to a reduction in supply (1945 and 1967), but in the year following the lifting of restriction demand returned immediately to that expected.

Two additional and larger reservoirs were constructed during these years. In 1980, the forecasted annual water demand for 2015 (given the expected increases in population and usage) was 31,040 ML (Knowles, 1984), more than double the amount of water used in 1980.

During the latter half of this period, when both the reticulated water supply and sewer were connected to all homes, the sewer flow was typically 50% of total water use, suggesting external water use, which will not be transferred to the sewer, was around half of the total. With the expansion of the sewer to all homes in addition to the reticulated supply and drainage system, at this time Ballarat can be described as a Drainage City.

4.4.4 1981–1999

Despite the forecasts of growth in water demand, the usage of water in Ballarat peaked in 1980 and then began to decline. Water restrictions temporarily assisted in reducing the demand for water in 1982, although such measures have been previously shown to have only short-term effects. Although there was adequate water availability at all times after 1983, the city's water use stabilised, and then began to decrease, with a per capita decrease of at least 20% between 1980 and 1999. The 1982 drought that prompted the introduction of water restrictions may have helped establish the idea that fresh water is, in fact, a scarce resource: an idea assisted by awareness campaigns such as 'Don't be a Wally with water'. Legislation requiring dual flush toilets on all new toilet installations was also implemented in 1984 (Melbourne Water, 2016). Residential allotment size also began to decrease from the 1980's with subdivisions becoming more common, however the existing housing stock resulted in the average of residential allotment size changing slowly.

Water quality and the impact of sewage treatment on downstream waterways became the focus of reporting during the 1980s. Although no additional water treatment plants were required in Ballarat, upgrades to the facilities improved the water quality of discharge. The sewer flow as a percentage of total water flow increased during this time, indicating less water was being used outside the home.

The reduction in water use, which suggests the introduction of a level of awareness of water as a finite resource, together with the priority given to the quality of the discharge from waste water treatment plants, shows it is reasonable to describe Ballarat during this time as a Water Way City, where the impact of the city on the surrounding environment is a consideration.

4.4.5 2000–2015

After the year 2000, water management has been dominated by a changing climate. A number of years of below average rainfall commenced in 1996, and by 2000 water restrictions were implemented. At this time, unlike previous periods of water restrictions, the restrictions remained in place for a number of years and became increasingly severe until 2008 when additional water became available and restrictions were eased. We note that although water restrictions had a significant impact on water use, the long-term trend in reduced water use began many years before restrictions were imposed. Between 2000 and 2008 per capita water use dropped below the longer term trend which appears to be constantly downward from 1990 to 2014, although it may now have stabilized at about 200 L per person per day.

The local water authority promoted water saving measures during the period of restricted supply. This included campaigns encouraging the installation of low-flow shower heads and dual flush toilets. External water use was disallowed for a number of years, which led to gardens with lower water requirements and the installation of domestic rainwater tanks. The sewer flow as a percentage of total water supply increased continually over the period of water restriction, supporting the idea that external water use was reduced: it is now less than 20% of the total water use in Ballarat. Non-domestic water use was also targeted through a water reduction in industry program. Further, a program to capture and reuse stormwater for external use within the city was undertaken: the most prominent example of which was the supply of water to Lake Wendouree. The water reduction measures were still in place when the unrestricted water supply again became available, and these may have hastened the longer term trend in reduced water use.

During this time, local water supplies were not able to provide adequate water for the city of Ballarat, so a 'superpipe' was completed, enabling the transfer of water from the northern Victorian irrigation district to Ballarat. This pipe forms part of the integrated water network around Victoria, which allows inter-basin transfers to achieve optimum allocations, and is now relied upon to meet the forecasted water demand for the next 25 years.

The long-term reduction in per capita water use, which resulted in a reduction in overall water use; increased awareness of water as a limited resource; and the use of alternative water supplies indicate that Ballarat at this time can most likely be considered a Water Cycle City, or at least, well on the way to achieving this status.

4.5 Discussion

The Urban Water Management Transitions Framework describes a relatively linear path through different phases of urban water management. While different phases can be distinctly seen in Ballarat's progression, they do not necessarily match with those described. This highlights the messy nature of history and development.

The reduction in water use from 1980 was unexpected. While researchers have expressed concern about the low level of implementation of alternative water supplies and the decisions taken to supplement local surface water, this data indicates communities have been responding to messages about the need for water conservation for an extended period.

4.5.1 Development compared to the framework

The conceptual model of the Urban Water Management Transitions Framework describes a city which first establishes a water distribution network, then sewerage followed by drainage before taking into account the surrounding environment and managing the Integrated Urban Water Cycle. While this representation describes the transitions that typically occurs, the data from Ballarat indicates that things occurred in a different order. Drainage was a particular issue for the newly developed gold mining town so resources were directed toward this issue. Conversely, while water supply was first established in the 1860's, sewerage was a lower priority and not commenced for more than 60 years.

Similarly, from the 1980's a strong awareness of the environmental impacts of water, and particularly waste water, can be seen. As Ballarat has many indicators representing a Water Cycle City it may be expected that strong environmental considerations would therefore impact later water supply decisions, favouring wastewater recycling or stormwater reuse options. However, when the local surface water supply was inadequate, an inter-basin transfer, the goldfields superpipe, was constructed. The security of the water supply and certainty of the outcome were favoured over more innovative solutions.

These examples highlight that while general trends may be visible, individual cities often make decisions based on their unique circumstances and consultative processes between different stakeholders. Responses are to local needs and situations rather than being in step with an overall philosophy. This is consistent with the findings of Furlong et al. (2016) who describe this process in water management, but also reference a seminal work by Lindblom (1959) which describes planning more generally as 'the science of muddling through'.

While decisions made at any time may be rational and based on the unique circumstances, they will however depend upon the criteria used for completing the comparative analysis. In Australia since the corporatisation of the water authorities in the 1990's (Furlong *et al.*, 2016) this has primarily been an economic assessment. Other considerations may be included as a hurdle, such as having an acceptable Environmental Impact Statement, but cost has been the ultimate determinant between options. In this case study alternatives to the superpipe were rejected due to the higher cost with no accounting for externalities or ecosystem services. Comparative analysis of factors other than cost is required to provide improved information so better informed decisions can be made.

4.5.2 Factors impacting decision making

Despite the common belief that water use had continued to increase up until restrictions in 2001, peak water use in Ballarat occurred in 1980. Apart from short term restrictions which

had previously had little long term impact on demand, there was unrestricted water availability. The factors which have influenced consumer water demand are not necessarily those which the authorities have used to estimate the required supply. The range of factors that influence decisions have been grouped under the Triple Bottom Line categories of social, environmental and economic in Table 4.1, and the impact of these on the water demand in Ballarat will be the subject of future work.

Table 4.1 – Factors impacting water use decisions

Category	Factor	Example
Social	Legislative	Requiring new residences to include dual flush toilets
	Awareness	'Don't be a Wally with Water'
	Lifestyle	Residential block size and garden type
Environmental	Climate	Rainfall and water availability
	Sustainability	Impact on rivers
Economic	Pricing	Water rates

4.6 Conclusion

This case study of Ballarat illustrates the messy path followed in the evolution of water management within a city. While a relatively linear path such as that described by the Urban Water Transitions Framework may be a useful summation of the general process, individual cities will make decisions based on their particular needs and situation.

When various water supply options are considered, hurdle criteria are often used to generate a short list. Following this, a comparative analysis is done, and typically an economic assessment is used for this. If other factors such as environmental impact are considered important, they need to be part of the comparative analysis if the best possible decisions on resource management are to be made.

The decrease in water demand in Ballarat from 1980, well before major long term restrictions were in place, indicates a better understanding of the factors that drove water use decisions by the community is required, and this could be significant for the future of urban water management decisions.

4.7 Acknowledgements

This work would not have been possible without the access readily given to the Central Highlands Water archive.

5. AN UNEXPECTED DECREASE IN URBAN WATER DEMAND: making discoveries possible by taking a long term view

Forecasting supply and demand is fundamental to the sustainability of the water system. The use data for Ballarat presented in Chapter 4 has been analysed to determine the contributing factors to changes over the long term. Factors considered in the analysis include rainfall, water availability and restrictions, price, indoor and outdoor use, environmental awareness and water awareness programs and government policy and legislation.

This work confirms research by others regarding the impact of price on water use with a very clear example, while providing new evidence regarding the importance of pricing structure. The chapter in the form presented here was published in *Water Policy* (D. Ebbs *et al.*, 2018c), a peer-reviewed international journal.

Ebbs, D., Dahlhaus, P., Barton, A., & Kandra, H. (2018). An unexpected decrease in urban water demand: making discoveries possible by taking a long-term view. *Water Policy*, 20(3), 617-630. (<http://dx.doi.org/10.2166/wp.2018.096>)

5.1 Abstract

Forecasting supply and demand is fundamental to the sustainability of the water system. Demand for urban water seems on an ever upward trajectory, with use increasing twice as quickly as population throughout the 20th century. However, data from Ballarat, a city in south-eastern Australia, shows that despite this conventionally held wisdom, total water usage actually peaked over 30 years ago. While the 1997–2009 ‘Millennium Drought’ had some effect, the decline commenced many years before. Initially, this was due to a reduction in external domestic water use which correlates well with an increase in water price. However, the effect was found to not be purely economic as the price was not volumetric based. Internal water use seems more affected by technological advances and regulatory controls. Interestingly, there was no relationship found between rainfall and water demand. The role of price, water reduction education programmes, water efficient technology and regulation, supports previous research that a multi-faceted approach is required when developing demand reduction policies and strategies. This finding emphasises the importance of understanding the component of consumptive behaviour being targeted, and ensuring that policies being implemented are appropriate for the desired behavioural change.

Key words | Domestic water use; External water use; Internal water use, Urban water demand; Water policy; Water price; Water price elasticity

5.2 Introduction

Forecasting supply and demand is fundamental to the sustainability of the water system. The demand for water increased dramatically during the 20th century, with worldwide domestic water use increasing six-fold, compared to a three-fold increase in population (Cosgrove & Rijsberman, 2000). The increases in living standards represented by the introduction of hot water availability, flushing toilets, showers and washing machines all contributed to increasing personal indoor use, with garden watering also impacting total domestic demand.

There has been a long-term interest in what drives consumptive water demand. Cochran & Cotton (1985) developed a model for Oklahoma taking water price, per capita income, rainfall, temperature and people per household into consideration. This compared favourably with the estimates by water utilities which until then had simply used population as the indicator of water use. Studies such as those by Hamilton (1983) and Berk *et al.* (1993) examined factors which induce water saving behaviours in households and include education, income and technological improvement while Aitken *et al.* (1994) also included attitudes, habits and values. Jorgensen *et al.* (2009) investigated 27 previous studies into behavioural models of water consumption and concluded that trust in the water authority and other consumers to undertake water savings is an important factor in changing behaviour. As the driest inhabited continent with increasing population and water use, Australia has been grappling with these problems since the 1970s with continued focus until the present day (Marlow *et al.*, 2013; Morgan, 2011; PMSEIC, 2007; Ward *et al.*, 2012).

In the context of the above observations, this study reviewed the progress of a city in relation to changes in the water use over time and identified which strategies correlate with these changes. Rainfall, water availability, outdoor garden use, allotment size, water price and tariff structure are considered. Identifying which of these correlate to changes in use, using a long-term, community-wide analysis, may assist other cities which are similarly attempting to manage the balance between water supply and demand. Water use data were studied for 135 years for Ballarat, an inland city in south-eastern Australia with a current population of 102,490 people (ABS, 2014). Anecdotal observations, supported by studies into water behaviour (Coombes *et al.*, 2014; Lowe *et al.*, 2014), suggested water use increased in Ballarat throughout the 20th century until the impact of the Millennium Drought, a 14-year period from 1997 to 2010 of below average rainfall in south-eastern Australia (BOM, 2015). Severe restrictions then forced technological and behavioural change to reduce usage. The long-term drought was considered to last adequate time for behaviour change to become embedded, a critical mass of people to be involved so water saving behaviour became normalised, and technological changes locked in. However, the longer record of water use data shows that usage peaked 20 years prior to the implementation of restrictions and had declined significantly prior to the drought.

The surprising result of long-term sustained water use reductions was analysed in relation to the factors which drove this. The study demonstrates the value in analysing long-term data, and the pit falls of assuming that demand is simply driven by population, availability or price. Further, the longer record shows the factors responsible for water demand to be complicated, with social, economic and environmental factors all influencing urban water usage.

5.2.1 Ballarat – A case study city

Ballarat is an inland, regional city in south-eastern Australia, 110 km from the Victorian capital, Melbourne. It is facing a range of water supply and demand issues typical of many cities throughout the world. The population has been constantly growing from 40,000 in 1945 (Australian Bureau of Statistics, 2014) to its current level, and is forecast to continue growing, reaching 140,000 people by 2035 (profile id, 2015). Ballarat was established and grew primarily due to the discovery of gold in the 1850s. Like other towns sited near a mineral resource, this meant it was not primarily established due to convenient water availability. Indeed, it is located on the intersection, and at the upper reaches of four catchments, which limits the available upstream harvesting area. Inter-basin transfers have been part of the water management system since its establishment.

The city is in a temperate climate zone, with average temperatures predicted to increase due to climate change, and average annual rainfall expected to decrease and become more variable (Ricketts & Hennessey, 2009). Over 80% of the urban water supply since 1974 has come from the Moorabool River located in a catchment adjacent to Ballarat (CHW, 2016). This is now rated as being in very poor to moderate condition along various reaches (DEPI, 2014). During the Millennium Drought, the surface water supply was supplemented by using groundwater and the commissioning and use of the Goldfields Superpipe for inter-basin transfers from remote catchments (CHW, 2016). As Victoria's largest inland city, and third in size overall, water use in Ballarat has been the subject of interest in that it can be considered a developmental site for potential changes in the broader community.

A water supply in the form of a standpipe was first provided to Ballarat in 1858, with usage data recorded from 1882. Metered domestic supplies and tariffs were introduced in 1915 with the sewerage system commencing in the 1920s. During the next 60 years, expansion of the system and economies of scale resulted in the water price reducing. From 1980, with increasing concern about the viability of supplying ever increasing quantities, the water price began to increase. In 1996, volume-based tariffs were introduced, with restrictions in place from 2000 until 2008 due to a sustained drought.

While Ballarat is a small, rural city and therefore not all observations regarding water management will be directly applicable to larger urban places, the issues of population growth, supply constraints, and increasing climatic and environmental pressures are common. The lessons from this case study using a long-term view and community-wide usage data can inform water management in other cities with similar issues.

5.3 Methods

5.3.1 Data sources

The amount of water supplied in the Ballarat region is recorded in the water utility annual reports. These are available in the Central Highlands Region Water Corporation (CHW) archives from 1882 until the present day (CHW, 2016). The Annual Reports have also been the source of information on reservoir levels, water restriction implementation, domestic and non-domestic use, sewer flow and revenue, including fixed and variable water charges.

Population data for Ballarat are available from census reports (Australian Bureau of Statistics, 2014; profile id, 2015; Victorian Government, 1857, 1884, 1894, 1904). Rainfall data have been sourced from the Australian Bureau of Meteorology (BOM, n.d.), information on groundwater wells (bores) from Southern Rural Water, and allotment sizes from the Department of Environment, Land, Water and Planning (DELWP), while the websites of the major Victorian urban water authorities, Melbourne Water, Yarra Valley Water, South East Water and City West Water, were used to identify relevant legislative and policy changes, along with the Building Standards and the Victorian Legislation archives.

5.3.2 Data management

As additional regions have been merged into what is now CHW, care has been taken to only include connections and water use which is currently covered by that reported as 'Ballarat and District' in the most recent Annual Reports. The number of connections shows no significant discontinuities which would represent data being suddenly included or excluded.

From 1882 until 1955, the water supplied was calculated by a summation of all metered water, including unpaid water. In 1956, metering was installed at the discharge of reservoirs which resulted in a step increase in the reported water use due to the inclusion of previously unmetered water, system losses and improved accuracy. A correction for this difference could be made by increasing all usage data prior to 1956 by 60%; however, for the sake of veracity and transparency, and as the change does not significantly impact any conclusions, the raw data are reported here.

While domestic and non-domestic water use has been reported for much of the time in question this has not always been the case. Between 1956 and 1997, the revenue (\$) and rate (\$/litre) for each was used to calculate the volume such that:

$$\text{Non-domestic water use (litres)} = \text{Non-domestic volumetric water revenue (\$)} / \text{Non-domestic water rate (\$/litre)}$$

The conversion factor of 4.54 litres per UK gallon has been applied to all volumetric data from 1882 until 1974.

As few people were connected to the reticulated supply during the early years, total population does not give an accurate comparative water use per head. Therefore, the number of connections to the water supply system and the number of people per house was used to determine water use per connected person. This technique has been used in other jurisdictions, such as Melbourne's water supply to determine the estimated population served by the water authority (MMBW, 1934).

The per person water use is calculated by:

$$\text{Domestic water use per person} = \text{Domestic water use} / (\text{domestic connections} \times \text{people per household})$$

The vast majority of water used inside the home (bathroom, laundry, kitchen and toilet) goes to the sewerage system, and most of the water used outside the home is lost to evaporation, transpiration, soil infiltration, groundwater recharge and stormwater runoff. Therefore, in places where there are separate sewerage and stormwater systems, as there are in Ballarat, the ratio of sewage flow to total water supplied gives an indication of the percentage of water use within the home. While there will be variation between years due to rainfall which inevitably affects the annual volume of sewage treated due to spillage and infiltration, trends over time will demonstrate changes in inside and outside water use. While no other published studies have been identified which use sewage volume as an indicator of internal water use, the process followed in this study is similar to the sewerage discharge factor which water authorities apply when charging volumetric sewage rates to unmetered flows (eg. CHW, 2016; CityWestWater, 2017). Other studies on water use behaviour using individual household information gain understanding from surveys and direct data collection (eg. Aitken *et al.*, 1994; Grafton *et al.*, 2011; Syme *et al.*, 2004; Wolters, 2014). While this provides a level of accuracy there are the issues of observer influence and a relatively small sample size, and individual sewer flow is generally not available to confirm results. Prior to 1970, as areas of the city were not seweraged, the ratio of the sewer flow to supply does not

reflect the percentage of water used inside the home. Therefore, only data from 1970 onwards is used in this section of the analysis. An assumption is made that the percentage of non-domestic water which flows to the sewerage remains constant over time at 80%, using the same factor which CHW use for determining the waste water rates for commercial customers (CHW, 2016). The results are not sensitive to this percentage with a 10% difference having less than a 1% impact on the estimate of internal water use, and no detectable change in the trend. The amount of non-domestic sewage flow is then calculated, and by difference the domestic sewage flow. The ratio of domestic sewer flow to domestic water use is then used to calculate the percentage of domestic indoor and outdoor water use, and the outdoor water use per person.

The total water revenue (fixed and variable) was divided by the total water supplied (excluding charitable, free or non-revenue water) to calculate a price per kilolitre, which was then converted to 2015 AUD (\$) using the Consumer Price Index (CPI) data (Australian Bureau of Statistics, 2016) and decimal currency conversion rate when appropriate. While there were many variable water rates for different users, this method gave a value which coincided with the most commonly applied domestic rate.

5.4 Results and Discussion

5.4.1 Potable water use

A continual increase in total potable water use (with a step change in 1956 as discussed) is seen from the 1920s, consistent with growing population and higher living standards. As described in the introduction, this was expected to continue until the end of the century; however, the increasing trend ends in the mid 1970s (Figure 5.1) with the peak usage occurring in 1980. As demand is so multi-variant it is unsurprising that it is difficult to define a clear-cut time when the decrease commenced, but it certainly stopped increasing sometime between 1976 and 1980. There is no detectable change in overall water use between 1980 and 1994, and then a significant reduction occurs during the six years prior to 2000, when restrictions commenced due to drought, and this decreasing trend continues until restrictions are lifted in 2008.

5.4.2 Domestic and non-domestic use

Non-domestic water use is a target for alternative water supplies as there can be businesses using high volumes, often with lower quality requirements. This, along with changes to the industrial and commercial landscape, can lead to higher volatility in demand. While the non-

domestic water use for Ballarat peaked in the 1980s and then declined (Figure 5.1), similarly to the overall consumption, it was not the driver of reduced usage. Since domestic usage is almost entirely the cause of overall reduction, it is the focus of this paper.

Factors in driving domestic demand identified in previous studies (Aitken *et al.*, 1994; Cary, 2008; Cochran & Cotton, 1985; Grafton *et al.*, 2011) include outdoor water use, rainfall and water availability, price, environmental awareness and water policy, which are explored more fully in the following sections.

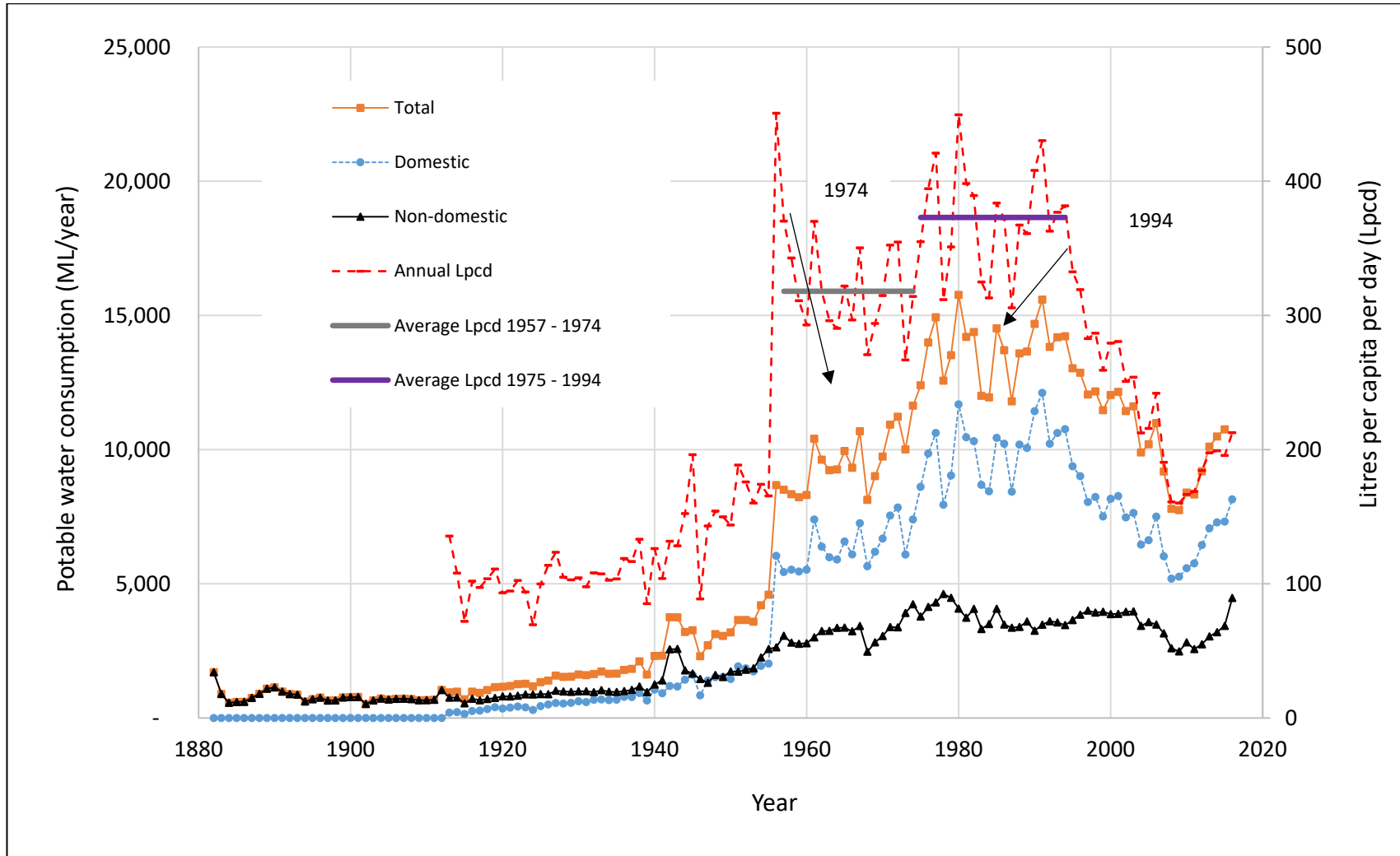


Figure 5.1 - Ballarat water use 1882–2016.

5.4.3 Water use per person

Managing total use and balancing supply and demand is the main objective for water utilities. However, when trying to understand demand and consumer behaviour, water use per person is a more appropriate measure. The water use per person per day shows a steady increase as expected until 1955 (Figure 5.1). The measurement changes, and the 1956 peak attributable to increased water use in filling Lake Wendouree, the rowing venue for the Melbourne Olympic Games, creates a discontinuity in the data at this time. From 1957 until 1994 there is an overall increase, although linear lines of best fit and testing of means between low and high periods show no statistically significant change between 1957 and 1974. Similarly, there is no change from 1974 to 1994. It is therefore best characterised as a step change from an average 318 litres per capita per day (Lpcd) to 373 Lpcd. There is a strong decline in water use from 1994, although it could also be observed as having declined from earlier peaks in 1980 or 1991, with a few higher years against the per capita water use trend. Potential causes for the reduction in use, including a tariff structure change in 1996, are discussed further in this paper.

By the time water use restrictions commenced in Ballarat in 2000 as a result of the Millennium Drought, water use had already reduced from 400 Lpcd in 1980 to approximately 270 Lpcd. A further reduction to 200 Lpcd occurred between 2000 and 2008 with restrictions in place during the drought. In Melbourne, the capital city of Victoria with a population of approximately four million people and 110 km from Ballarat, the annual water consumption increased until 1998. From then until 2010 water use declined, before stabilising over the past few years (Melbourne Water, 2015). The domestic water use is currently 166 litres per person per day or 17% less than Ballarat.

The decline in water use in Ballarat and Melbourne is similar from 2000 onwards, and could be attributed to similar climate influences that were being experienced. However, the decline in water use in Ballarat between 1980 and 2000 is incongruent, confirming the potential for lessons to be drawn from the analysis of the drivers of demand.

5.4.4 Rainfall, water availability and restrictions

If water is not available it cannot be consumed, and conversely, as water supplies increase in size and distribution becomes more common, use also tends to increase. An increase in ability to supply to Ballarat came with the commissioning of the Lal Lal reservoir in 1973 and this corresponds to a consumption increase at this time. Lack of rainfall and any subsequent implementation of restrictions will result in demand reductions, and restrictions in 1982 may

be considered to have contributed to the reduction in use at that time. However, restrictions were used in Ballarat in 1946 and 1967, and while they had the desired impact of temporarily reducing demand in those years, they had no long-term impact, leading to the assumption that restrictions during 1982 would not have been the reason for the longer-term reduction in use. Restrictions were again in place between 2001 and 2008, and generally increased in severity (DEPI, 2015), until water diverted from northern Victoria (via the Goldfields Superpipe) became available. The restriction schedule initially limited, and later banned, external household water use. The length of time for which these restrictions were in place has been considered to be significant enough to permanently change people's water use behaviour (Lowe *et al.*, 2014), to the extent where water demand would not recover to pre-restriction levels, even after all restrictions were lifted.

From the initial stages of trying to model urban water demand (Cochran & Cotton, 1985) rainfall has been identified as a factor which may negatively correlate with water use. It seems logical that with higher rainfall, less is required for lawns and gardens. However, rainfall anomaly versus water use data from 1957 until 2016 (Figure 5.2) show there is no correlation ($R^2 = 0.03$) and even when outliers are removed, which correspond to the transition from drought years with restrictions to high rainfall (1967, 1982, 2010 and 2011 as shown), there is a slight positive correlation, but the R^2 value of 0.11 is still very low. A positive relationship between rainfall and use may be related to consumer behaviour whereby there is a level of comfort with high use when there is plenty of water available. Note here that the rainfall anomaly is calculated as the departure of the annual rainfall from its long-term average value for the location concerned.

The reduction in water use throughout the 1980s and 1990s cannot be conclusively attributed to either less external water being required due to high rainfall, or the impact of a low rainfall period with restrictions. Despite the expectation of a relationship between rainfall and usage, no correlation was found, which is consistent with studies over six years in Phoenix, Arizona (Campbell *et al.*, 2004) and Germany (Schleich & Hillenbrand, 2009). Over the period of this study, changes in technology and community behaviour have resulted in much larger changes than any which can be attributed to rainfall variation. While it may seem counter-intuitive, the data for Ballarat suggest rainfall was not a particularly important factor in the change in annual water use.

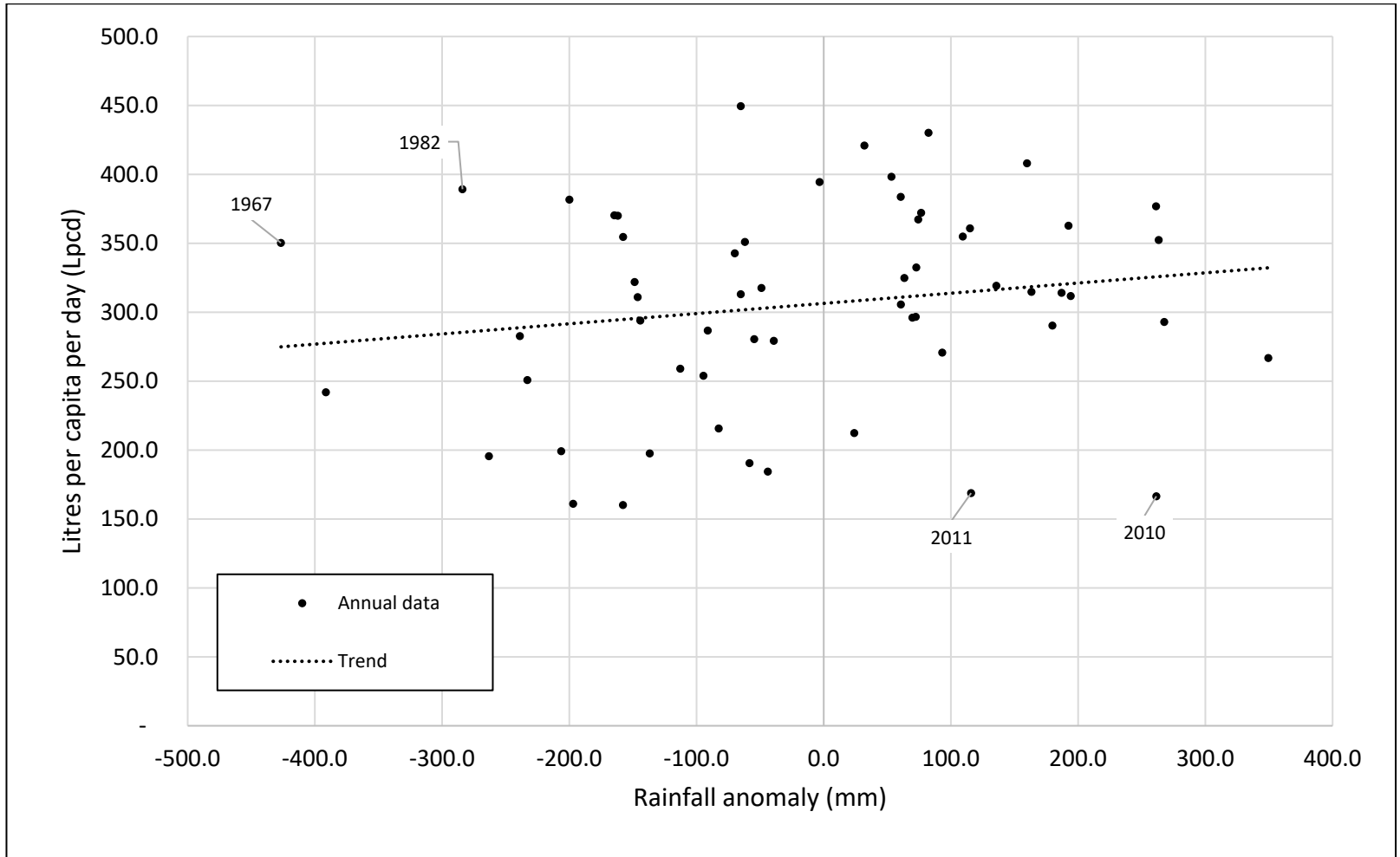


Figure 5.2 - Ballarat water use per person versus rainfall anomaly.

5.4.5 Outdoor water use versus total water use

External water use is often considered more discretionary than internal use (Sadalla *et al.*, 2014), although Syme *et al.* (2004) argue that the amenity achieved through maintaining a garden is important for many in the community. As such, it has been regularly included in domestic demand models (eg. Aitken *et al.*, 1994; Jorgensen *et al.*, 2009; Sadalla *et al.*, 2014; Syme *et al.*, 2004). Comparing the total sewer flow to the total water supplied to Ballarat shows a steady increase (Figure 3), which is considered to reflect the higher percentage of total water being used inside the home. The external domestic use per person shows a decrease from 1980, corresponding to the timing of the overall decrease in water use in the city.

Allotment size is intuitively related to outdoor water demand, and has been shown to be a significant variable (Syme *et al.*, 2004), although those with smaller lawns have been shown to be less efficient (Landon *et al.*, 2016). Comparing allotment size in Ballarat from 1956 to 2016 to water use produces a weak linear correlation ($R^2 = 0.33$). However, this simply demonstrates both variables increased and then reduced at the same time, without establishing causation. The average people per home reduced linearly over this period, unlike water use which increased and then decreased.

The impact of other potential causes of reduced external water use such as garden aesthetics, drought-resistant plants and water efficient design cannot be identified using these data. Given these constraints, it is not possible to quantify the effect of block size and separate its effect on water use with these data, while recognising the large impact external water use had on the overall water used reduction.

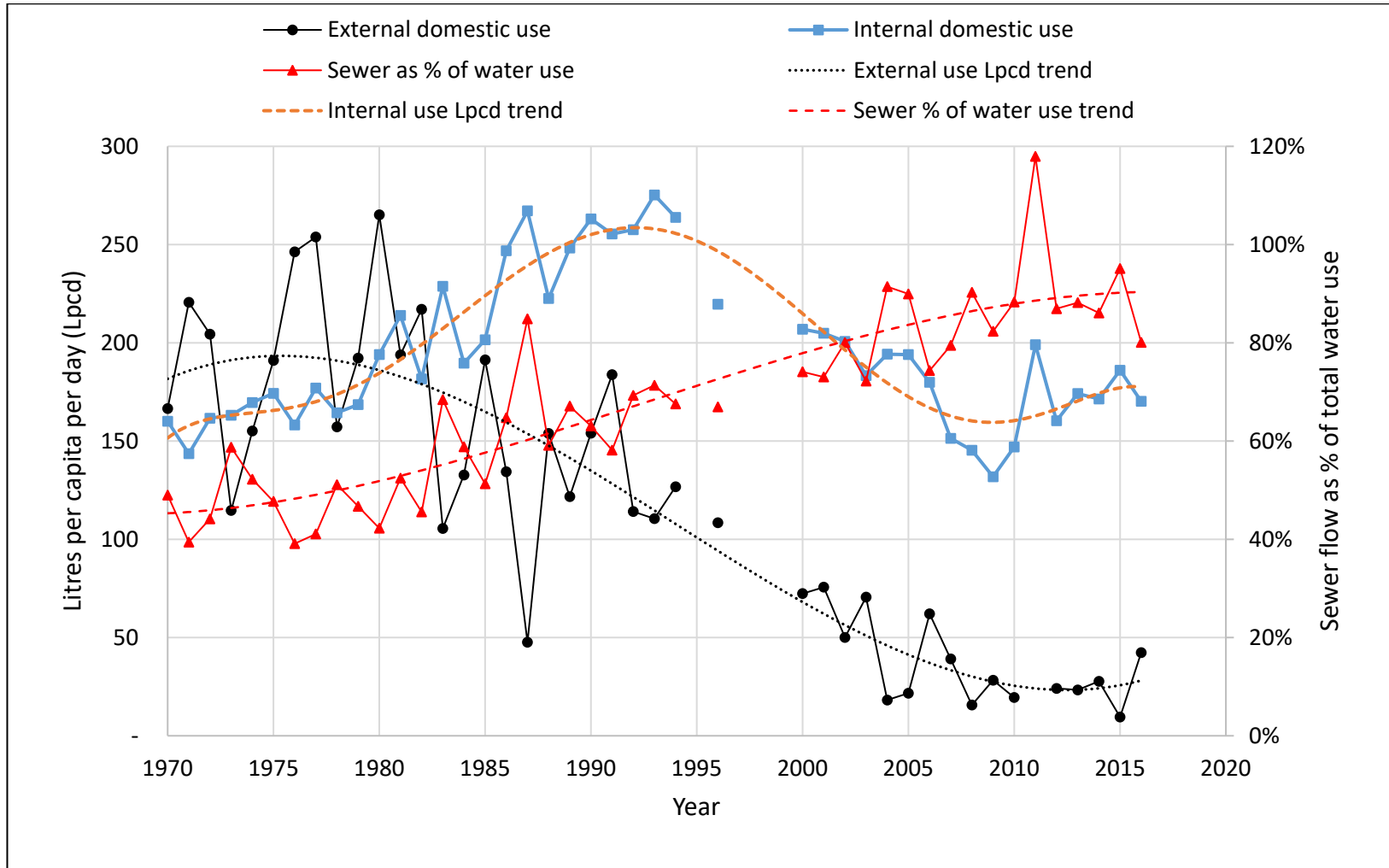


Figure 5.3 - External and internal domestic water use in Ballarat.

Outdoor water use is generally non-potable, leading to the possibility that alternative water supplies have been increasingly used rather than there being an actual reduction in water use. However, the use of rainwater tanks in the 1980s was still discouraged and it is unlikely they had a significant impact at this time (Gardner & Vieritz, 2010), and the number of domestic groundwater supply wells also showed no increase. Grey water re-use systems such as laundry water to the garden would have a similar effect in reducing external use of potable water; however, this would result in a simultaneous reduction in both sewer flow and water supply, with little change in the relationship, counter to the data. There is, therefore, no indication that non-potable water use was the cause of water use reductions prior to the Millennium Drought.

The data on internal and external water use over time demonstrates a major shift in the consumption pattern, with external use accounting for more than half of all use in the 1970s but reducing to typically 10% since 2005, after which it remains relatively constant. While some of the difference may be attributed to restrictions from 2001 to 2008, there has been a long-term and sustained change in consumer behaviour.

While external use decreased from 1980, as did the overall water use, internal domestic use per person continued to increase throughout the 1980s, with the voluntary programmes in place at that time having little effect on non-discretionary use. Internal use peaks and declines from the mid 1990s (Figure 3), suggesting that the restrictions imposed, technological changes and general awareness during the protracted Millennium Drought period had more impact on the internal, less discretionary, water use as may be expected.

5.4.6 Water price

Demand for water has generally been considered inelastic with regard to price, although this does not mean price does not affect usage, only that the percentage change in use will be less than the percentage change in price (Olmstead & Stavins, 2009). The price for water in Ballarat has been calculated by dividing the total water revenue made up of fixed and volumetric charges by the total quantity of water supplied. From 1915 to 1996, the fixed component of the water price was 95% of total domestic revenue, and the variable domestic portion never exceeded 11% of the total domestic charge in any year. Up until 1980, network expansions and economies of scale enabled the price to be reduced and then maintained in real terms allowing for inflation (Figure 4). The resulting relationship between price and usage is therefore a result of higher volumes rather than a driver of increased use. From 1981, increases in real price correlate with a decrease in water use (Figure 4). While this

trend appears continuous between 1981 and 2006, there was a significant change to the tariff structure in 1996. The fixed price component of the tariff was reduced to 25% of the total, with a volumetric charge making up the remainder. Despite the change in tariff structure, the data from 1996 to 2008 produces the same usage versus price slope as the period from 1981 to 2008.

The 1981–2008 correlation between price and usage (Figure 4, $R^2 = 0.64$) shows a 200% price increase resulting in a 35% decrease in overall water consumption, a price elasticity of -0.17 which is a little higher than the result previously reported for Sydney, Australia of -0.11 (Abrams *et al.*, 2012). However, it has been demonstrated that external use is more price sensitive than internal use (Thomas & Syme, 1988) and in Ballarat the decline during periods of price increase was heavily weighted to external use. Therefore, if external water use only is considered, the price elasticity is -0.4 which corresponds to two meta-analyses in the U.S. which found an average of -0.5 (Espey *et al.*, 1997) and -0.41 (Dalhuisen *et al.*, 2003), but the latter study also concluded this depended on the pricing structure. This supports the view that a price incentive will have the greatest effect on discretionary use, but much less effect on essential use. Post-2009, with external use being at an effective minimum, further price increases had no effect, demonstrating that there is a limit to reductions that can be achieved through price incentives.

Demonstrating the price sensitivity of water is not unexpected, with simple economics suggesting that a higher price would encourage less use. However, it may be expected that the change in pricing structure in 1996 from a 95% fixed rate to a 75% variable rate would alter the price versus usage sensitivity; however, this did not occur in Ballarat at the time.

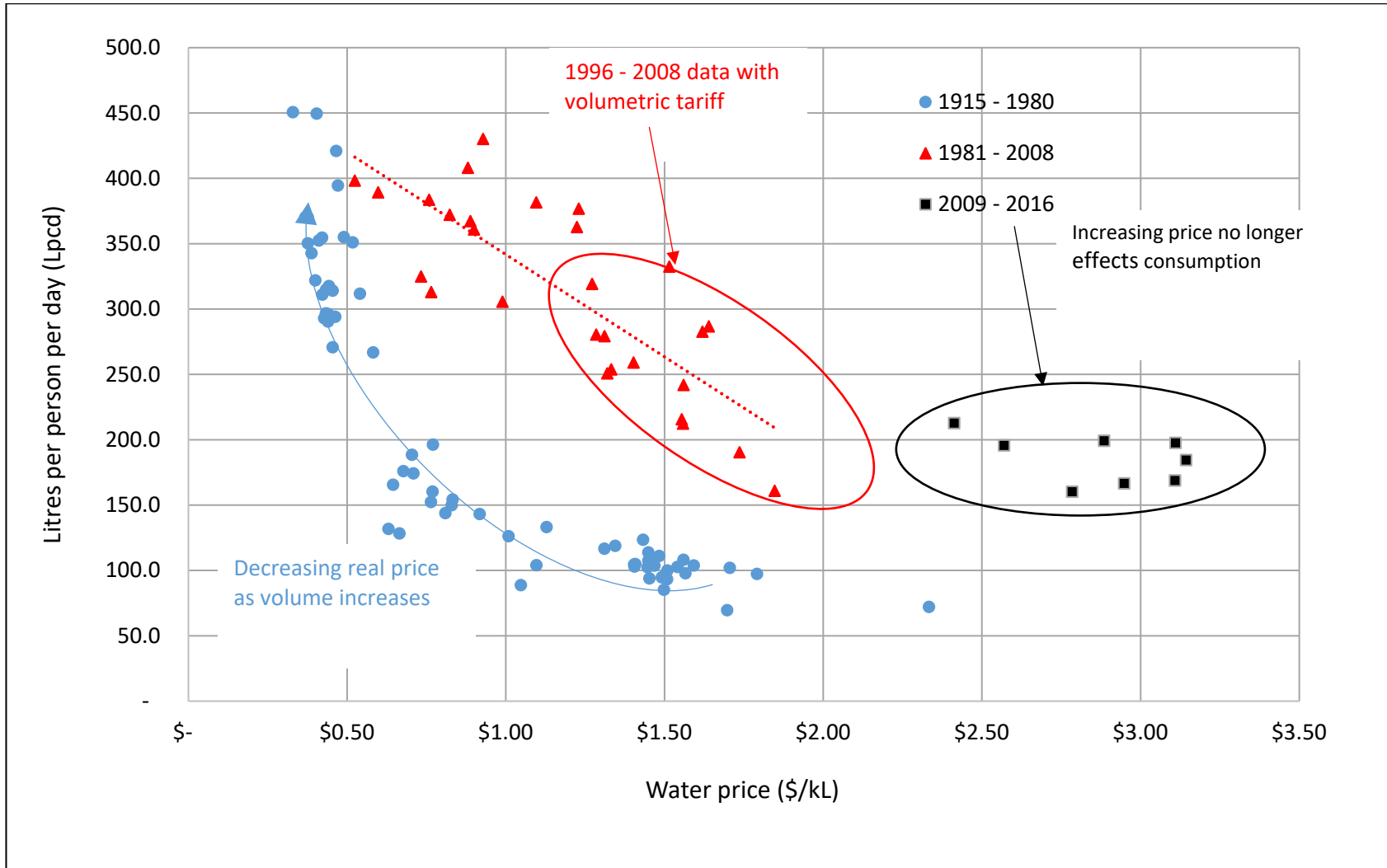


Figure 5.4 - Ballarat water consumption versus price.

5.4.7 Environmental awareness and water awareness programmes

The attitude of customers towards the environment has been found to impact the amount of water they consume in some studies (eg. Grafton *et al.*, 2011). Awareness campaigns are used to increase public understanding, change attitudes and alter behaviour.

The Millennium Drought and the associated concerns about climate change and the long-term water supply resulted in many programmes aimed at water efficiency (Australian Government, 2016; SWEP, 2006; WELS, 2005). However, this was well after the reduction in Ballarat's water use commenced. While they do not correspond to the overall water use reduction which was initiated by reductions externally, these programmes do show an effect on internal water usage.

While attitude to the environment has been hypothesised to impact the water consumption of individual consumers, Nieswiadomy (1992) suggests that conservation attitudes do not significantly affect consumption at a community level, while Landon (2016) states that the mechanism for it to have an effect is poorly understood. Wolters (2014) also shows that environmental concern is not a good indicator of environmental behaviour. As this study is historical without comparative groups to determine what altered behaviour, it is not possible to categorically determine whether environmental attitudes were a contributor to reduced water consumption. However, we do know (from the water price analysis) that price alone is not the cause.

It is reasonable to consider that a level of environmental awareness is required for long-term behavioural change with respect to water, and that this combined with pricing produced change throughout Ballarat. The idea that incentives are required in conjunction with awareness campaigns is consistent with the review by Cary (2008). Awareness, campaigns for change and incentives are all required to produce a long-term effect – individually they can plant the seed for change, but unless the ground is fertile they will not grow.

5.4.8 Government and policy changes

Legislators can impact demand by ensuring higher water availability or imposing restrictions and pricing policy, enacting building regulations that target water saving devices, providing incentives for water re-use programmes, and altering the structure of and interaction between water utilities. Significant governance changes in the water industry in Victoria in the 1990s may be both a reflection of and a reason for a significant focus on water supply and management.

In Ballarat, stormwater harvesting for public open space watering and filling the city's main recreational lake has been implemented, although this commenced in 2006 and the total impact on usage was expected to be less than 2% (Rossiter, 2013). The dual flush toilet was invented in Australia in 1982 (Powerhouse Museum, 2016) and became compulsory in all new homes in Victoria from 1984. However, this change would take years to have a significant impact, and other legislative changes were associated with the Millennium Drought years after the reduction in Ballarat water use commenced.

5.5 Conclusions

This research has highlighted that it is possible for a city to achieve sustained reductions in water use over a period of 35 years, seemingly irrespective of the changes in water availability during drought and relative water surplus. With water security and the impacts of urbanisation a major issue across many modern cities, this is an example that can be used to demonstrate what can be achieved, although larger cities with differing circumstances will need to develop their own methods for implementation.

The separation of internal and external domestic water use in an historical study, without access to any individual or household information, was possible by using sewage flow data as a proxy for internal water use. In a city where sewerage and stormwater systems are separate, effectively no water used outside the home goes to the sewerage and the majority of internal water does, this is considered to be a robust approximation approach. Despite intuitively considering external demand would be inversely correlated to rainfall, this study confirms work by others, showing a negligible relationship.

Initially, reductions in use were driven by changes in external water use and corresponded to price increase/tariff changes. However, the effect cannot be purely economic, as the price of water was not based upon the volume used. The effect of overall, rather than variable, price on water demand is not without precedent (Nieswiadomy, 1992), and it is surmised that price acted as a change agent, in conjunction with general awareness of water and environmental issues and policy changes. Consequently, the total price, rather than a price based on consumption, was the most important factor. Internal water use, considered to be much less discretionary, showed little sign of responding to price changes as may be expected.

The impact of both price and non-price policies together having an impact has been studied by a number of authors (eg. Barrett, 2004; Olmstead & Stavins, 2009; Renwick & Green, 2000; Reynaud, 2013), who conclude that mixed policy implementation is effective in reducing water consumption. This would be supported by the results of this research on Ballarat. Pricing policies and awareness programmes combined to effectively minimise the

water use outside the home, where reductions could be made relatively easily without compromising comfort and at minimal cost. The encouragement to use water-saving devices was then effective in reducing the internal water use. This supports a multi-faceted approach to water demand reduction which requires economic incentives, awareness programmes and policy approaches encouraging the reduction of water use. It demonstrates the importance of understanding the behaviour being targeted, and ensuring that the incentives or policies being implemented are appropriate.

The reduction in water consumption over such a long period was incongruent with the expectations. It demonstrates that water authorities and communities can respond to the pressures inherent in the water supply system in a timely manner. It shows that communities will respond to changes and constraints in the services provided, adjusting behaviour to meet a new paradigm, with no apparent loss in facility. It is also a reminder of the difficulties in forecasting resource demand, which is multivariate and complex; however, increasing water use that has been associated with a more affluent and urbanised society need not continue to inherently grow. While meeting water demand is a major, ongoing issue, it need not be an ever increasing problem.

5.6 Acknowledgements

This work would not have been possible without the access readily given to the Central Highlands Water archive, particularly Rosalie Poloski and Phil Anstis. Thanks also to Rick Pope and Arthur Dallas from Land Victoria, for producing a unique data set on allotment size by year for the municipality. The comments from three independent and anonymous reviewers are appreciated, and resulted in a more concise article. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

6. A WATER BALANCE APPROACH TO INVESTIGATE STREAMFLOW COMPLEXITIES DOWNSTREAM OF AN URBAN CENTRE

The potential for stormwater to supplement existing water supplies while mitigating the environmental impacts of excess flow requires determination of the water generated from impervious surfaces, in excess of that which would occur in undeveloped conditions. While forecasting and modelling has been used to predict what may occur, an analysis of the change in water flow due to urbanisation that has occurred will provide evidence.

To enable the change in river flow due to urbanisation other causes of river flow changes must be removed. An annual water balance removing all transfers to and from the catchment allows the changing runoff to be calculated. Identified causes of changes in runoff can be due to impervious surfaces, other change in land use, climate, depression storage and interruption of surface flow, retention and use in rainwater tanks and groundwater baseflow.

This chapter presents a method for undertaking this analysis of the urban water flow, and the results for Ballarat. The initial findings were presented as two peer-reviewed conference papers (D. Ebbs *et al.*, 2018a, 2018b), and the chapter as presented has been peer-reviewed for *Urban Water* (an international journal) and resubmitted in the form presented here (D. Ebbs *et al.*, 2018d), which addresses the comments made by the peer-reviewers.

As discussed in Chapter 3, Methods, one limitation of a case study is the transferability to other cases. Work undertaken to reproduce the results from Ballarat in other Victorian cities, chosen due to the similarities in climate, water availability, data and governance, have been included as an Addendum to Chapter 6.

Ebbs, D., Dahlhaus, P., Barton, A., & Kandra, H. (2018a). *Exploring a flow regime and its historical changes downstream of an urbanised catchment*. Paper presented at the WSUD 2018 and Hydropolis 2018, 10th International Conference on Water Sensitive Urban Design, Perth, Australia.

Ebbs, D., Dahlhaus, P., Barton, A., & Kandra, H. (2018b). *Losing stormwater: 60 years of urbanisation and reduced downstream flow*. Paper presented at the 10th International Conference on Water Sensitive Urban Design: Creating water sensitive communities (WSUD 2018 & Hydropolis 2018).

Ebbs, D., Dahlhaus, P., Barton, A., Kandra, H. (2018d). A water balance approach to investigate streamflow complexities downstream of an urban centre. *Urban water*, Submitted.

6.1 Abstract

Integrated Urban Water Management (IUWM) offers multiple benefits however, while the peak runoff from urban surfaces is known to increase, the impact on the total streamflow is more variable and less well understood. Studies of urban hydrology regularly assume additional runoff related to the increase in impervious surfaces.

A method for analysing the impact of urbanisation on annual downstream river flow is presented coupling a water balance with hydrologic runoff modelling enabling calculation of the relative contribution to changes in river flow.

A case study demonstrates that after 60 years of increasing urbanisation, despite expectations, the downstream river flow has decreased due to variations in climatic conditions, peri-urban development and groundwater baseflow.

While the study demonstrates a technique for improving the understanding of the complexity of urban hydrology data availability may prove difficult, reinforcing that appropriate monitoring is required if unintended consequences of IUWM implementation are to be avoided.

6.2 Introduction

IUWM) offers multiple benefits that span improved amenity in the lived environment, better environmental outcomes for receiving waterways and additional water resources that can supplement, or even replace, current supplies (Bell, 2015; Ross, 2014; Wong, 2006). However, to ensure its success, it must consider the broad context of catchment management and the cumulative effect of all factors including river health.

The effects of urbanisation which include increased magnitude and frequency of peak flows, and the resultant impact this has on the morphology of receiving waterways and the riparian landscapes, have been established with research over a long period (Fletcher *et al.*, 2012; Klein, 1979; Shuster *et al.*, 2005). However, while the peak runoff from urban surfaces is known to increase, the impact on the total streamflow is more variable and less well understood. Early research showed urbanisation can decrease streamflow when groundwater contribution is significant (Otto *et al.*, 2002), cause little change (Wiitala, 1961) or increase flow significantly (Jones, 1971). The change in total flow is dependent on the catchment, infiltration, evaporation, higher temperatures due to the heat island effect (Arnfield, 2003) and the directly connected imperviousness (Burns *et al.*, 2015).

The implementation of IUWM is increasing and this will begin to have impacts at the municipal scale. While there is good evidence (Fletcher, Shuster, *et al.*, 2014; Hamel *et al.*, 2013) on implementing Water Sensitive Urban Design (WSUD) at the development scale, and how this can ensure storm flows do not exceed pre-development level, IUWM is typically expected to deliver other benefits such as reducing demand from centralised potable water supply systems. However the effect of total annual water flow downstream of an urban catchment is less clear and not as widely researched.

Although there have been published urban water balances which estimate the additional resource, they generally use the area of impervious paving and varying infiltration to calculate flow (Hardy *et al.*, 2005; Mackay & Last, 2010; Mitchell *et al.*, 2007). This does not account for all the changes in the water balance and impacts of urbanisation on the river systems, the complexity of which is becoming recognised (Bhaskar *et al.*, 2016). To consider the total impact of IUWM, the stream flow of the receiving waterway ideally needs to be measured directly upstream and downstream of the urban area, i.e. leaving and entering the system boundary. Actual changes in streamflow over time can then be compared with expected changes due to known causes, and the differences attributed to various effects of urbanisation. Including the downstream flow will 'close' the water balance, giving greater certainty to estimates which calculate run off based on impervious surface area. Typically, and dependent upon the context, the data required may include:

- Precipitation on the city and catchment

- Bulk transfers of water in/out of the city
- Water consumption within the city
- Treated wastewater volumes to receiving waterways
- Extractions from waterways
- Streamflow data for the receiving waterway
- Groundwater recharge, abstraction and change in storage
- Evapo-transpiration and soil moisture

Changes in streamflow can then be attributed to known causes such as;

- Increased runoff from impervious surfaces
- Rainfall and evapotranspiration
- Rainwater tanks
- Dams and depression storage
- Baseflow changes

Change is underway with the management of stormwater, with particular emphasis on the protection of downstream waterways, however the measurement of other impacts of IUWM, in particular the ability to substitute potable water supply, is limited. This paper presents a procedure for undertaking a water balance of an urban area to determine the change in runoff over time, identifying causes which may impact the downstream flow, and quantifying the contribution of each of these. It demonstrates its use with a case study. This provides new insights that challenge the prevailing theory of urban water runoff and demonstrates a method for measuring impact of urbanisation on a catchment. Although neither the type of data gathered, the use of a water balance nor the modelling presented in this work is unique, the process for coupling these and application to determining the impact of urbanisation on a receiving water seems not to have been widely published in the literature.

6.3 Method

The procedure for understanding the impact of urbanisation on total annual river flow has three stages.

1. Urban water balance to determine the river flow due to runoff
2. Selection of potential impacts on change in river flow to be studied

3. Calculating the contribution of each impact to the change in river flow

A flow chart of this process is shown in Figure 6.1 with data requirements shown on the right, and the techniques used on the left. A general method is described for each step with details of the process undertaken for the case study described.

Understand impact on River due to urbanisation

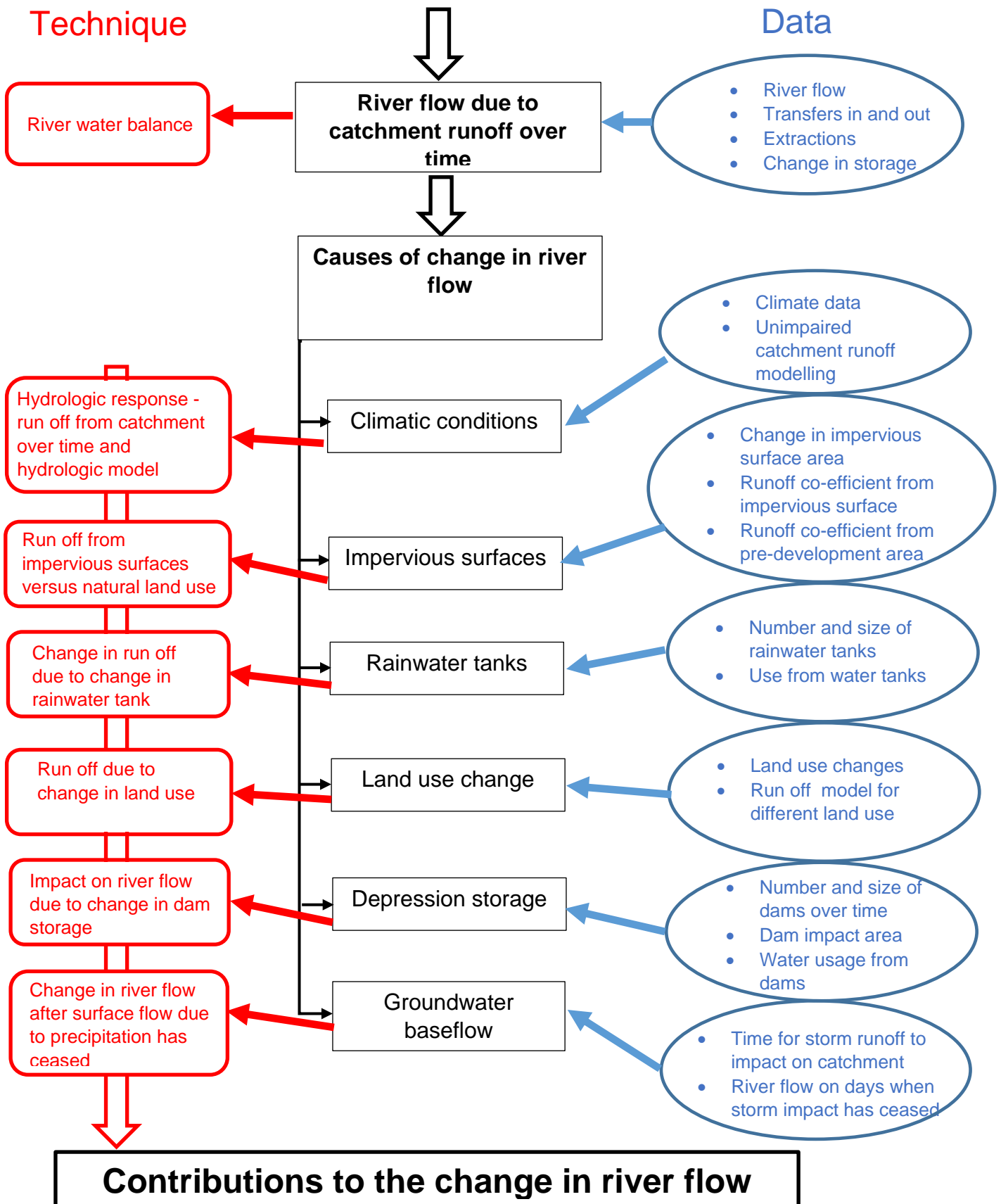


Figure 6.1 - Procedure for calculation the impacts of urbanisation on downstream river flow

6.3.1 Case study city: Ballarat

Ballarat is a city in south eastern Australia (37.5622° S, 143.8503° E) of 103,964 inhabitants in 2016 (Australian Bureau of Statistics, 2017). It is facing many of the typical water issues confronting communities throughout the world. It has grown from 50,930 people in 1957, and is forecast to continue growing to 140,000 people in 2030 (profile id, 2015). Existing surface water supplies are limited and there is a reliance on inter-basin transfers for supply (CHW, 2016). Groundwater has been used to supplement supply in times of extreme drought. Harvesting stormwater using Managed Aquifer Recharge has been trialled (CHW, 2016), rainwater tanks are standard in new homes, and WSUD features have been installed in some housing developments. The location of the city was determined primarily due to the discovery of gold, and it sits in the upper reaches, and at the intersection of, five separate catchments (Figure 6.2).

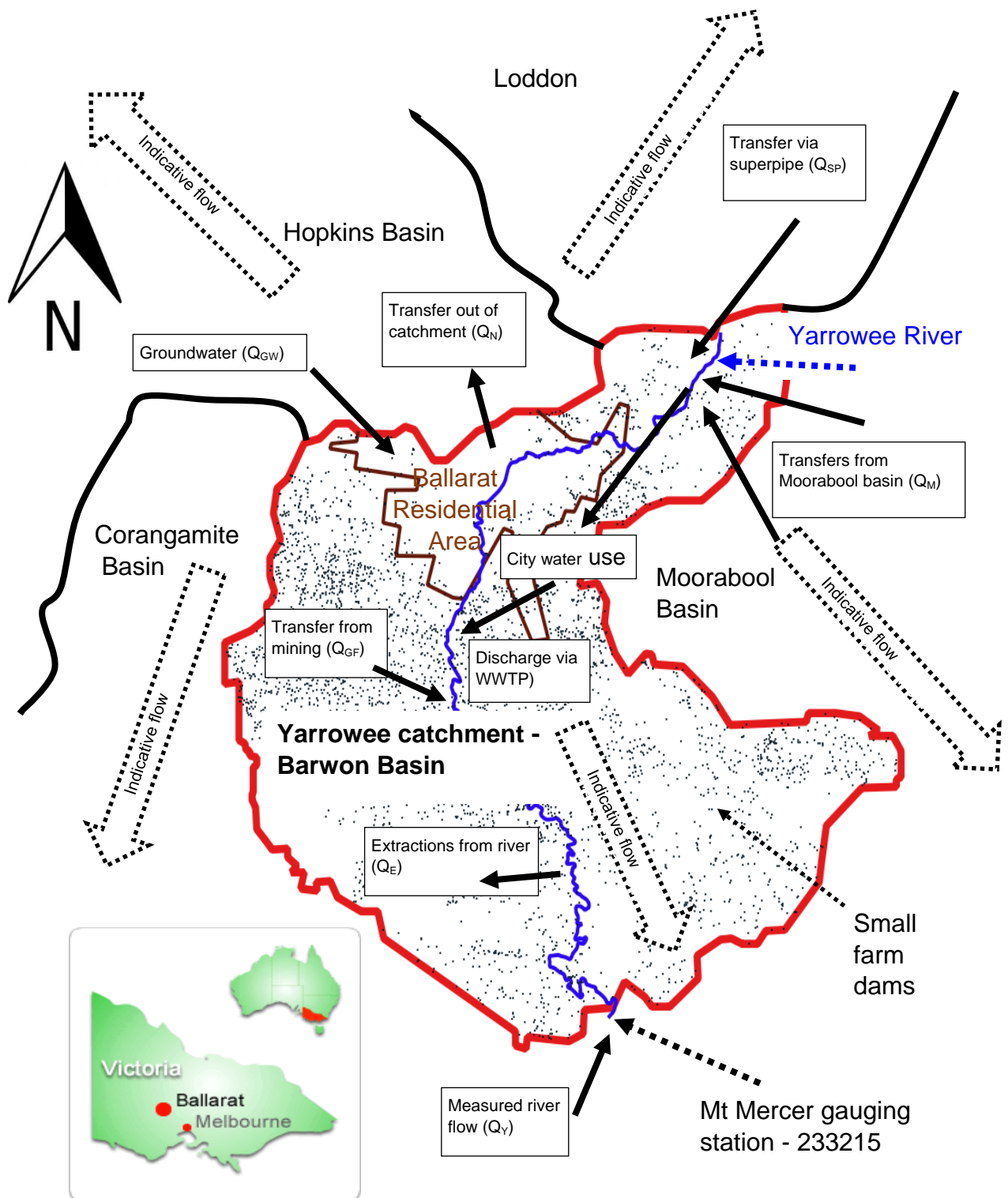


Figure 6.2 - Ballarat location, water basins and transfers.

The waterway from which the initial supply was taken, and into which the majority of stormwater and wastewater now flows, is the Yarrowee River. However, from the 1860's reservoirs have been established in the adjoining Moorabool River catchment, with water supply security now dependent on bulk transfers from northern Victoria via the 'Goldfields

Superpipe'. The sewerage network commenced in 1922, and the initial treatment plant, Ballarat South, discharges to the Yarrowee River, and currently processes 2/3 of Ballarat's wastewater. The 'Ballarat North' treatment plant has processed the remaining waste since being established in 1972 and discharges into the Hopkins River Basin. In addition mine de-watering from Ballarat Goldfields is transferred into the Yarrowee River. Groundwater, sourced from upper aquifers outside the Yarrowee River catchment, was used to supplement supply during the Millennium Drought (1997 – 2008).

A number of monitoring stations (river gauges) have been established on the Yarrowee River, however, the current one on the Leigh River at Mt Mercer (233215) has been operating continuously in its present form since 1956 (DELWP, n.d.-d). This is approximately 29 km south of Ballarat, with a total contributing catchment area of 593 km². While a river measurement point closer to the city would be more sensitive to the effect of urbanisation, measurements from this gauging station demonstrate the overall impact on the catchment due to growth and spread of the city. Significant peri-urban development in the form of hobby farms and lifestyle properties occurs throughout the catchment. Farms, forests and timber plantations comprise the majority of the remaining land uses. There is no irrigated farming and the licensed extractions from the river are for relatively small volumes of stock and domestic water uses.

A growing city in a temperate climate with 60 years of data available on transfers into and out of the city boundaries and the river from a variety of sources, including water treatment plants and remote catchments, enable a water balance to be constructed that can allow an analysis of the impact of urbanisation on the receiving waterway. The use of annual data for calculating the system water balance removes seasonal effects. Seasonal variations, peak flow magnitude and frequency analysis, and rate of change are all important determinants of urbanisation impact and IUWM and can be measured using different time scales. However, when assessing the total water resource available to supplement supply, an annual time frame provides appropriate information.

6.3.2 Water balance

Urbanisation can result in water transfers which impact the river flow, and to determine the changing river flow due to rainfall on the catchment, these transfers must be calculated. Bulk transfers across the catchment boundary, diversions for use, extractions and additions including treatment plant discharge and change in storage must be considered on an annual basis. The overall river flow, which must be measured if a closed water balance is to be completed, is a combination of these components and the runoff from rainfall on the catchment. In Ballarat recent data was accessible via Victorian Water Accounts, and earlier

information was contained within the Annual Reports of the local water authority (CHW, 2017). The annual flow is shown in Equation (1) for the Yarrowee River as measured at the Mt Mercer gauge, and shown schematically in Figure 2.

$$Q_y = Q_{CR} + (Q_M + Q_{GF} + Q_{SP} + Q_{GW}) - (Q_N + Q_E) - S_y \quad (1)$$

Where

- Q_y = Yarrowee River flow (recorded)
- Q_{CR} = river flow due to rainfall (stormflow + baseflow)
- Q_M = transfers from the Moorabool River catchment
- Q_{GF} = Ballarat Goldfields mine discharge
- Q_{SP} = transfers from remote river basins (via the Superpipe)
- Q_{GW} = managed transfers from groundwater
- Q_N = transfers out of the catchment via the north treatment plant
- Q_E = extractions from the river for farm stock and domestic use
- S_y = change in storage of reservoirs from the Yarrowee River catchment

The river flow due to rainfall is the effective runoff from the catchment and is the rainfall minus evaporation, transpiration, consumptive use and changes in groundwater storage.

Q_{CR} is the variable that will most change due to urbanisation and the associated increases in impervious catchment area. As there is data available for all other components, Equation (1) can be rearranged to calculate Q_{CR} in Equation (2).

$$Q_{CR} = Q_y - (Q_M + Q_{GF} + Q_{SP} + Q_{GW}) + (Q_N + Q_E) + S_y \quad (2)$$

6.3.3 Hydrologic response

The hydrologic response is the translation of rainfall into runoff and stream flow in the catchment. The annual average hydrologic response (HR_{AA}) over time demonstrates the change in overall river flow volume due to rainfall, and can be calculated by dividing the river flow due to catchment runoff by rainfall and catchment area (Equation 3).

$$H_{RAA}(\%) = 100 \times \frac{Q_{CR}}{\text{Rainfall} \times A} \quad (3)$$

Where

HR_{AA} = annual average hydrologic response

Q_{CR} = river flow due to rainfall on the catchment (ML/year)

$Rainfall$ = average rainfall over the catchment (mm/year)

A = catchment area (km²)

While hydrologic response will be affected by urbanisation, the runoff from the catchment is dependent on climatic conditions as these effect variables such as evapotranspiration and soil moisture. The expected change in runoff due to changes in temperature and rainfall without any change in land use must be modelled, and if the difference between the actual river flow and predicted runoff was to change over time, it may be possible to relate this to the changes in the catchment and demonstrate the impact of urbanisation on the total river flow.

6.3.4 Hydrologic model

The Australian Water Resources Assessment Modelling System (AWRAMS) is a grid based (0.05°), integrated hydrologic model developed by the Australian Bureau of Meteorology (BOM) and Commonwealth Scientific and Industrial Research Organisation (CSIRO) (Elmahdi *et al.*; Frost *et al.*, 2015; Hafeez *et al.*, 2015; Viney *et al.*, 2015). Data from this modelling system was used for the present case study rather than undertake additional, or specific modelling for this catchment. It can provide evapotranspiration, shallow, deep and groundwater moisture at depths to six metres and runoff since 1911 in Australia based on unimpaired catchments at a daily time step. Parameters describing soil, vegetation and topology enable a water and energy balance to be completed for each hydraulic unit. Of the 49 parameters included in the model, 29 are fixed based on known conditions with 20 adjustable for calibration. Calibration and validation used 595 river basins across Australia. While this broad scope gives strength in the amount of data available and robustness, it can mean local calibration issues are not considered, however published calibration results indicate performance is similar to locally calibrated models (Frost *et al.*, 2015). Data was provided by the BOM for the Barwon River Basin for daily, monthly and yearly intervals from 1911 until 2016.

The Yarrowee River flow anomaly has been calculated by subtracting the actual river flow from the predicted runoff in Equation 4.

$$Y_{RA} = Q_{pred} - Q_{CR} \quad (4)$$

Y_{RA} = Yarrowee River flow anomaly (ML/year)

Q_{pred} = Runoff predicted by AWRAMS (ML/year)

Q_{CR} = river flow due to rainfall on the catchment (ML/year)

6.3.5 Water from urbanisation due to impervious surfaces

The additional runoff from impervious surfaces within the catchment can be calculated by determining the increase in area of impervious surface, and the difference in runoff characteristics between the hard surface and the original catchment which it replaces. The original catchment runoff has been calculated in the prior section, hydrologic response, as HR_{AA} , while the hydrologic response of an impervious surface, HR_I , is available from literature. The increase in impervious surface can be estimated by use of aerial imagery if available, or records indicating the number and size of buildings, roads and other surfaces being constructed. The calculation for determining the additional runoff due to the imperviousness of urbanisation is given in Equation 5.

$$ARO_n = \Delta IS_n \times Rainfall_n \times (HR_I - HR_{AA}) \quad (5)$$

Where ARO_n = Additional runoff in year n (ML)

ΔIS_n = Change in impervious surface area in year n (m^2)

HR_I = Hydrologic response of impervious surface (%)

It has been calculated that impervious surfaces can result in 95% of rainfall becoming stormwater (Niemczynowicz, 1999), however in this study a more conservative hydrologic response of impervious surfaces was chosen as 90%.

The number of dwellings each year has been obtained from connection data reported by the urban water utility annual reports (CHW, 2016). Average new dwelling size over time is available from Australian Bureau of Statistics (ABS) from 1986 and for single years in the 1950's (Australian Bureau of Statistics, 2013a). A constant percentage increase per year in dwelling numbers was assumed between 1957 and 1986. The ratio of total impervious area (roads, driveways, carparks and houses) to residential dwellings in other research have been estimated to be 3:1 (Frazer, 2005), however aerial imagery accessed via Google Maps (Google Inc.) indicated that within Ballarat, this ratio was 2:1 due to the lower density of urban development compared with major cities. Hence this more conservative estimate was used.

6.3.6 Rainwater tanks

Rainwater tanks are designed to capture runoff from roofs and make this available for use, thus altering the flow of water to the river. All water captured in rainwater tanks is assumed to reduce streamflow as it will either substitute for potable water discharged via the treatment plant or be used externally and assumed to contribute to evapotranspiration. The number, size and use of tanks installed can be used to calculate impact, although this data can be difficult to obtain.

In Ballarat, the use of rainwater tanks, which had been discouraged following implementation of a centralised supply due to the risk of contamination (Gardner & Vieritz, 2010), was encouraged during the Millennium Drought (CHW, 2016), particularly for garden watering and toilet flushing, and enables them to achieve a higher sustainability rating (Victorian Building Authority, n.d.). Research has been undertaken elsewhere into how widespread rainwater tanks have become and the effect this has on water consumption (Gardiner, 2010; Gardner & Vieritz, 2010). Previous work found a reduction in external water use in Ballarat between 1996 and 2010 (Ebbs, 2017), and 50% of this reduction and 50% of toilet flushing has been assigned to the impact of rainwater tanks, which gives a result consistent with previous reports into the use of rainwater tanks in Ballarat which estimated up to 40% of potable water could be substituted (AECOM, 2011; Coombes *et al.*, 2014).

6.3.7 Land use change

As different land use, farming practices and forestation results in different runoff, estimation for the change in river flow due to these practices must be accounted for. Hydrologic models allow for different land uses, so this may be complementary to the modelling completed to understand changes in climate.

Surrounding the Ballarat urban area, land use changes over the study period have not been significant, with similar levels of forestation and farm use still predominantly sheep and some cropping. Therefore, no estimation of the change in river flow due to land use has been included. The major change in non-urban development is the peri-urban fringe which has been included in the section on depression storage.

6.3.8 Farm dams – depression storage

A feature of urbanisation which can impact runoff is the development of a peri-urban fringe where larger allotments are purchased for lifestyle residences, often with a dam for watering animals, garden, wildfire control or aesthetics, the extent of which can be seen surrounding Ballarat in Figure 2. While the change in storage for reservoirs has been accounted for in the water balance, the number of small dams can result in a significant disruption to surface flow. To calculate this impact the area of catchment with interrupted flow, the volume and area of dams and usage of water from these must be calculated.

STEDI (Spatial Tool for Estimating Dam Impacts) is modelling software that calculates the impact on runoff due to dams (Nathan & Lowe, 2012), completing a water balance around each dam, each time step, accounting for inflow, rainfall, evaporation, removals and bypass. The model can predict the impact of future dams or effect of previously installed dams. The requirements of STEDI software are:

- Stream flow
- Rainfall
- Evaporation
- Dam size
- Dam catchment (% impacted)
- Usage (% storage used annually)

Stream flow, rainfall and evaporation are all available at daily time steps from the Bureau of Meteorology (BOM). The number and size of dams in the Yarrowee catchment has been calculated using visual counts from aerial photographs (Victorian Government, n.d.-a), Google Earth, and current data confirmed using the Victorian Water Asset Database (DELWP, n.d.-c). The area of catchment impacted by dams and the amount of water used are the two variables impacting this water balance. GIS data indicates up to 68% of the study catchment may be affected, and estimates of usage vary between 20% and 70% per annum. To understand the impact of these variables a sensitivity analysis was completed

varying affected catchment area between 30% and 70%, and usage from 20% to 80% at 10% increments, resulting in 35 cases.

The increase in peri-urban development around Ballarat in the past 30 years coincided with the Millennium Drought. At the end of the drought, the majority of dams, new and old, were empty or near empty, resulting in much higher surface and depression storage than had ever been the case. For the purpose of this study it has been assumed that these were all constructed in 1997, analogous to their impact. Streamflow from 1957-1996 was recalculated assuming dams were in place, and 1997 – 2016 estimates completed assuming dam removal, resulting in 70 predictions for daily impact over the entire flow range. Maximum and minimum daily impacts were then applied throughout the time series to calculate the potential range presented.

6.3.9 Baseflow

The baseflow contribution to the stream flow can be estimated by analysing the river flow during periods where stormflow has ceased to have an impact, the time for which can be calculated in catchments as shown by Equation 6 (Linsley *et al.*, 1982).

$$t \text{ (days)} = 0.827 \times A^{0.2} \quad (6)$$

The time estimate for a storm flow to still be providing surface runoff to the Yarrowee River is 3.0 days. The flow after 4 or more consecutive days of no rain with the contribution from the Ballarat South WWTP removed has been used to estimate the baseflow. The groundwater situation is complex and further research into the changes caused by the urbanisation of Ballarat and the river flow is planned.

6.4 Results

Despite the population of Ballarat increasing from 51,000 to 78,000 between 1957 and 1996 (Australian Bureau of Statistics, 2017), and the number of residences doubling from 18,000 to 37,000 in the same time (CHW, 2016), there was no significant trend in river flow during that period. A best fit using linear regression and a difference of means test shows the average runoff reducing, but this is not statistically significant. However the last 20 years has seen a significant reduction in the river flow.

6.4.1 Water Balance

The Yarrowee River flow, as measured at the Mt Mercer gauge downstream of Ballarat from 1957 to 2016 is shown in Figure 6.3. The river flow due to rainfall on the catchment (Q_{CR}) is also shown, and can be seen to have a similar profile. Transfers into and out of the river have resulted in a nett gain of 6,000 ML/year of flow in the Yarrowee River, primarily due to transfers from the adjacent Moorabool River catchment and other systems to maintain Ballarat's water supply. Overall, while the transfers do vary from year to year depending on the availability of various forms of water, the overall impact is relatively constant, with actual and calculated river flow being almost indistinguishable.

6.4.2 Hydrologic response

The average annual hydrologic response (HR_{AA}) shows a similar pattern to the river flow (Figure 6.3). While the average annual rainfall in the past 20 years is 84% of that from 1957 – 1996, the river flow reduced to 34% with the HR_{AA} reducing from 13.2% to 4.9%, a statistically significant change in the rainfall - runoff relationship.

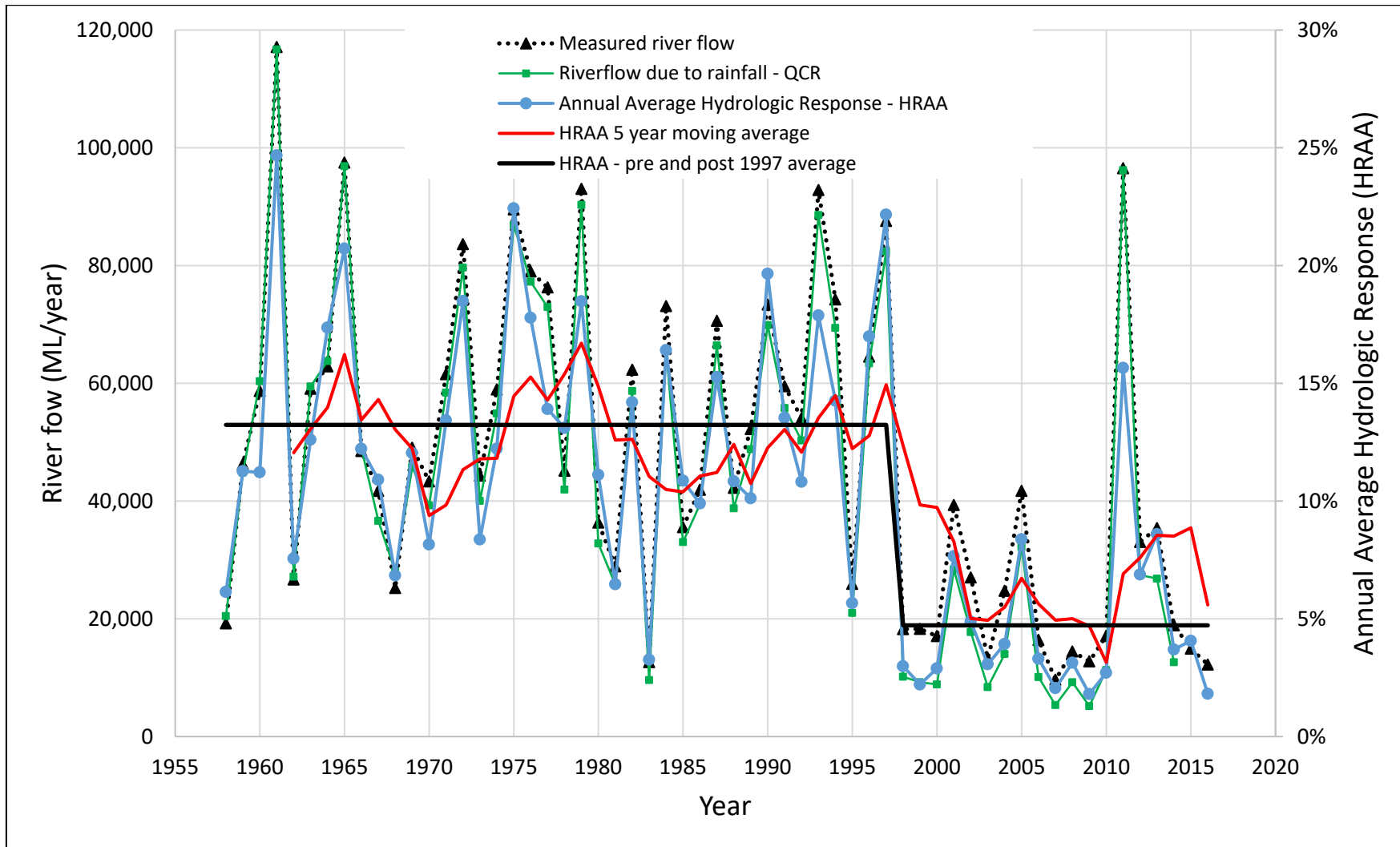


Figure 6.3 - Yarrowee River flow and annual average hydrologic response

6.4.3 Hydrologic model results

During the initial 40 year period of recorded flow data for the Yarrowee River, there is good correlation between the modelled runoff data from AWRAMS and the actual measured flow (Figure 4) with a difference of means test showing no statistically significant difference at a 99% Confidence Interval (CI). Between 1997 and 2016 the modelled runoff was 16,500ML/year higher than the measured streamflow which is statistically significantly different at a 99% CI.

6.4.4 Water from urbanisation

The number of dwellings in Ballarat increased from 17,000 to 50,000 (CHW, 2016) and the average size from 110 m² to 210 m² (Australian Bureau of Statistics, 2013a) between 1957 and 2016. This resulted in predicted additional stormwater runoff of over 6,500 ML per year by 2016, or about half of Ballarat's total potable water use per year, which is similar in volume to the net import of water from other catchments to the flow of the Yarrowee River (11% of the 1957 – 1996 average river flow and 28% of the post 1997 average).

6.4.5 Rainwater tanks

Average per person water use reduced from 290 Litres per capita per day (Lpcd) in Ballarat in 1994 to 200 Lpcd in 2010 (Ebbs, 2017), with 70 Lpcd of this reduction due to outside water use. Toilet use has been estimated to contribute 35 Lpcd to overall water use in Australian cities (Loh, 2003). Assuming 50% of the external water use reduction and toilet flushing has been achieved through the use of rainwater tanks, the estimated impact is 60 Lpcd, resulting in an annual stream flow reduction of 1,500 ML/year. This is equivalent to 16 % of the total potable water use in Ballarat however it is just 4% of the observed streamflow reduction and is only a minor cause of the reduction in the flow of the Yarrowee River.

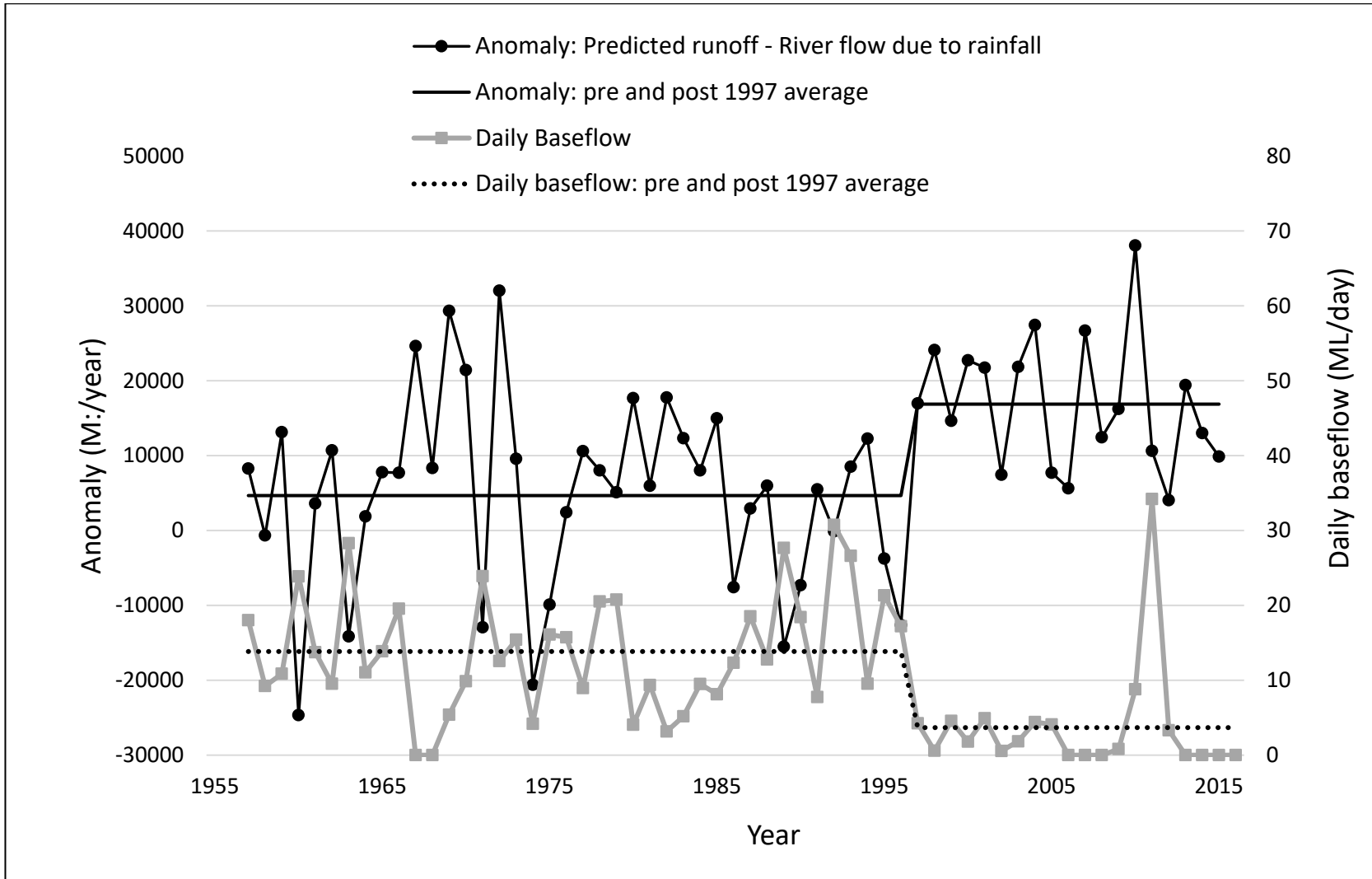


Figure 6.4 - Predicted and actual runoff anomaly and baseflow by year

6.4.6 Impact of farm dams and depression storage

There are currently 5107 identified farm dams within the Yarrowee River catchment upstream of the Mt Mercer gauge. The impact of these is predicted to be higher during times of low flow as dams will be commensurately emptier, and more flow will be subsequently captured following a rain event. The estimated effect is a reduction of 21 ML/day (7,500 ML/year) with a range of 3,000 to 12,000 ML/year.

6.4.7 Baseflow

The baseflow of the Yarrowee River is shown in Figure 4, with the 1957 – 2016 average of 14 ML/day dropping to 4 ML/day in 1997 – 2016. This reduction of 10 ML/day (4,000 ML/year) is 6% of the 1957 – 1996 average flow and 17% of the post 1997 average flow.

6.4.8 Relativity of impacts

The relative size of the impacts from the potential causes of the reduction in the Yarrowee River flow are shown in Figure 5. The average river flow for the two periods demonstrates the reduction from 58,000 ML/year to 23,000 ML/year. The solid black bar shows the predicted impact for each variable, while the hashed bar indicates the maximum effect estimated. A minimum effect has also been calculated but for clarity of the Figure has not been shown. In each case the error bar is symmetrical about the predicted value.

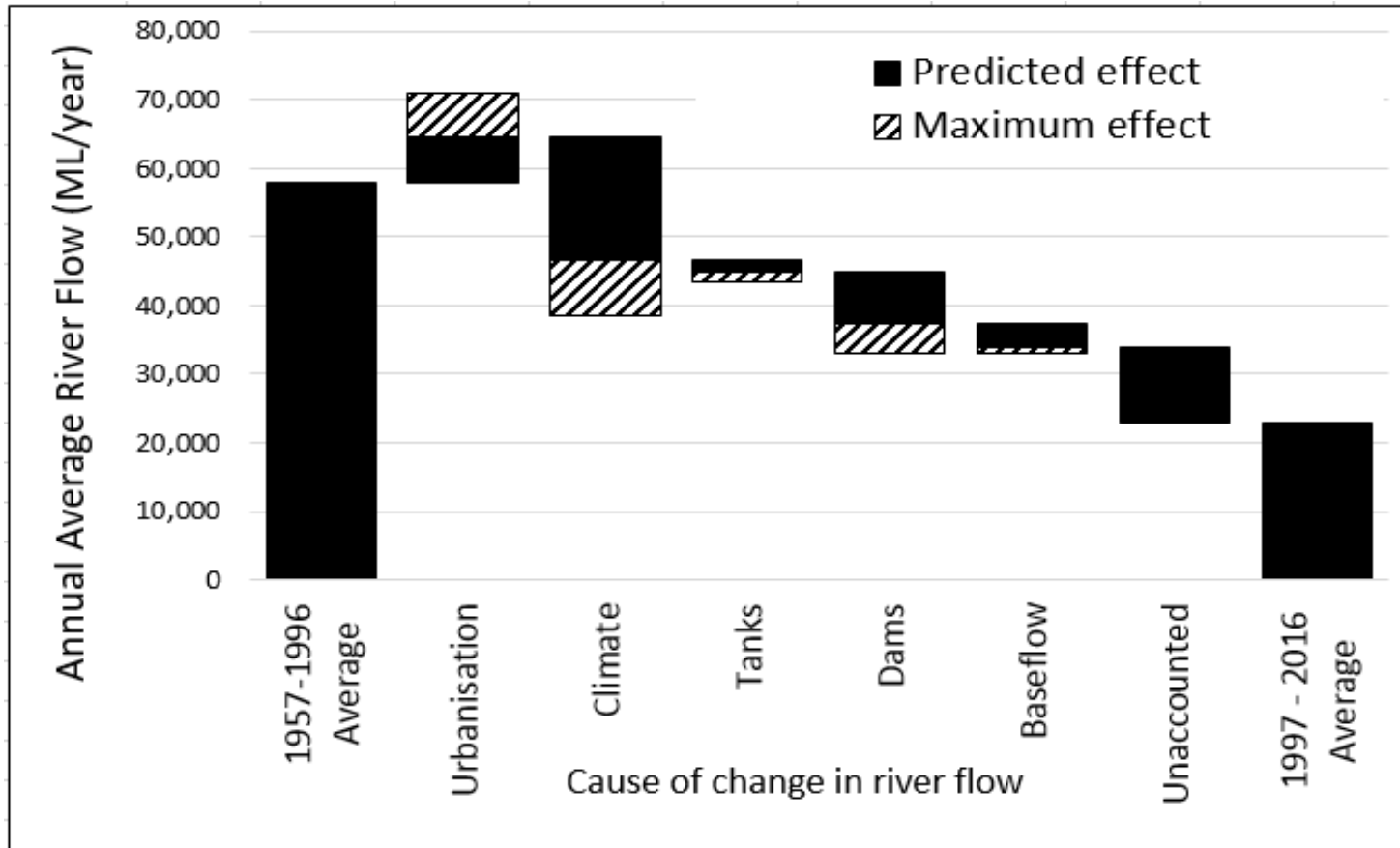


Figure 6.5 - Annual average flow of the Yarrowee River and impact on flow of various causes.

6.5 Discussion

IUWM offers the potential, among other benefits, of utilising runoff from urban areas to supplement the water supply. For this to be realised, an understanding of the complex impacts of urbanisation on the total annualised flow of a river downstream of a city is required. However, there are few publications of this nature in the academic literature where the water balance of a city is 'closed', with most studies estimating runoff based on the change in impervious surfaces.

This work has demonstrated a procedure linking the catchment runoff modelling and downstream river flow with many impacts of urbanisation; that is impervious surfaces, rainwater tank installation, peri-urban development and groundwater baseflow. This enables the calculation of the relative impacts of these on the overall water balance.

In the case study presented, despite significant increases in urban area no change in overall river flow could be detected over a forty year period, and the reduction in flow over the past 20 years was statistically significantly greater than expected from hydrologic modelling. The impacts on the catchment that have resulted in river flow reductions are far greater than any increase in river flow due to urbanisation. In Ballarat, the majority of the reduction has been due to changes in runoff associated with rainfall, temperature and soil moisture, and peri-urban development and the increase in dam storage.

Reproducing this work in other catchments, even in Victoria with a similar water management framework, has proved difficult due to data availability from urban catchments. Along with accuracy of the predictions this prevents more definitive conclusions being drawn, highlighting the need for greater understanding of urban hydrology if unwanted effects of IUWM are to be avoided. It demonstrates the complexity of the urban water balance, and that the cumulative effects of changes to the environment can only be known if the flow of the receiving waterway is appropriately monitored, whereas so often it is assumed. Improved monitoring of all the components of the water balance would assist in assessing the impacts of implementing IUWM actions, with flow monitoring downstream of cities being essential if the full effects are to be understood.

6.6 Conclusions

One of the commonly understood tenets of IUWM is the capture and use of stormwater flows from impervious surfaces that are in excess of natural flows otherwise generated from an undeveloped catchment. This article demonstrates a procedure for assessing the complex interactions of the urban water balance by measuring the flow of rivers downstream of cities in conjunction with runoff modelling. However while this technique can be useful in any urban setting, the required data is often not readily available. Therefore, the ability to monitor the progress of IUWM is limited. The multiple effects of urbanisation and incremental impacts from IUWM such as decentralised systems, changes in land use on the peri-urban fringe and the effect of groundwater from reduced infiltration cannot be accounted for as they have been in this study.

With the increasing importance of identifying alternative water sources and the encouragement of IUWM into day-to-day water resource planning activities, it will be necessary to implement an appropriate monitoring regime to ensure that well intended actions do not lead to unintended consequences. The historical origins of water resource monitoring and the difficulties usually encountered in changing or adding to government funded monitoring regimes presents a barrier to developing a systems monitoring approach for the impact of IUWM.

6.7 Acknowledgements

Thanks to Dr. Alison Oke from the Australian Bureau of Meteorology who supplied the AWRAMS modelling data used in this assessment, and Rosalie Poloski and Phil Anstis from Central Highlands Water, and the access readily given to their archive.

6.8 Addendum to Chapter 6 - Comparison of cities

The case study information presented in the previous three chapters has been based on the City of Ballarat. As discussed in Chapter 3, one limitation of this methodology is the transferability of any conclusions. It is therefore useful to investigate other cities in a similar way to determine if the findings are based on unique circumstances.

As water use, management, data and river flow is dependent upon climate, availability and socio-political conditions it was determined the most appropriate comparisons would be other Victorian cities where these can be considered broadly similar.

Victoria has a heavily skewed population profile. In 2017, 78% of the state's population of 6.15m lived in the Melbourne Metropolitan area (Australian Bureau of Statistics, 2017). The next three cities are Geelong (approximately 300,000 people), Ballarat and Bendigo (100,000). Following this the largest independent cities (not part of the wider Melbourne metropolis) are within the Murray Darling Basin irrigation area, an extremely tightly monitored and controlled waterway with greater annual allocations than average river flow, where the river flow is controlled by releases and extractions. Remaining cities in Victoria are below 25,000 people where the population and urban density is considered too low to be representative of the impacts being investigated. Comparisons have therefore been limited to the four largest Victorian cities.

6.8.1 Water use

Melbourne water use and water use per person was obtained in a similar manner to Ballarat, through the annual reports of the appropriate managing authority. The Melbourne and Metropolitan Board of Works was established in 1890, however the earliest records on monitored use available from the State Library of Victoria commenced in 1915 (Melbourne and Metropolitan Board of Works, 1915 - 2017).

Geelong water use was not able to be accessed for an adequate period to make it meaningful. As in Ballarat, Melbourne and other jurisdictions, the name and scope of the water authority has changed over time since commencing as the Geelong Municipal Water Trust in 1908. Records since 2004 are available for Barwon Water, and those from 1985 – 1993 reports from the Geelong and District Water Board can be accessed. The only other data located was 1955 – 1964 reports for the Geelong Waterworks and Sewerage Trust in the National Library Canberra, and the additional data did not justify the expense of retrieval. Therefore Geelong has been excluded from the comparison.

Bendigo is within an irrigation area, and from 1906 - 1984 water was managed by the State Rivers and Water Supply Commission, and now is the responsibility of Coliban Water. While some records are available for all this time, domestic water use was not separated until 1971, and was again unavailable for 1977 – 1979.

Unlike Ballarat, the total water use in Melbourne and Bendigo continued to increase until 2000 (Figure 6.6) when restrictions were imposed due to the Millennium Drought, as had been expected. The pattern after 2000 is similar, with a decline (sharpest in Bendigo) and then an increase after restrictions were lifted following rain in 2010. The water use per person (Figure 6.7) shows a similar pattern for Bendigo, with no decline until 2000.

However, in Melbourne the decline in per capita water use commences in 1990, with a steady period prior to this in a similar manner to Ballarat. Prior to this, the increase in water use per capita is much smoother for Melbourne up until 1980.

The ability for Melbourne to achieve a decline in water use per person prior to the introduction of water restrictions supports the conclusion that long term, sustained reductions can be achieved.

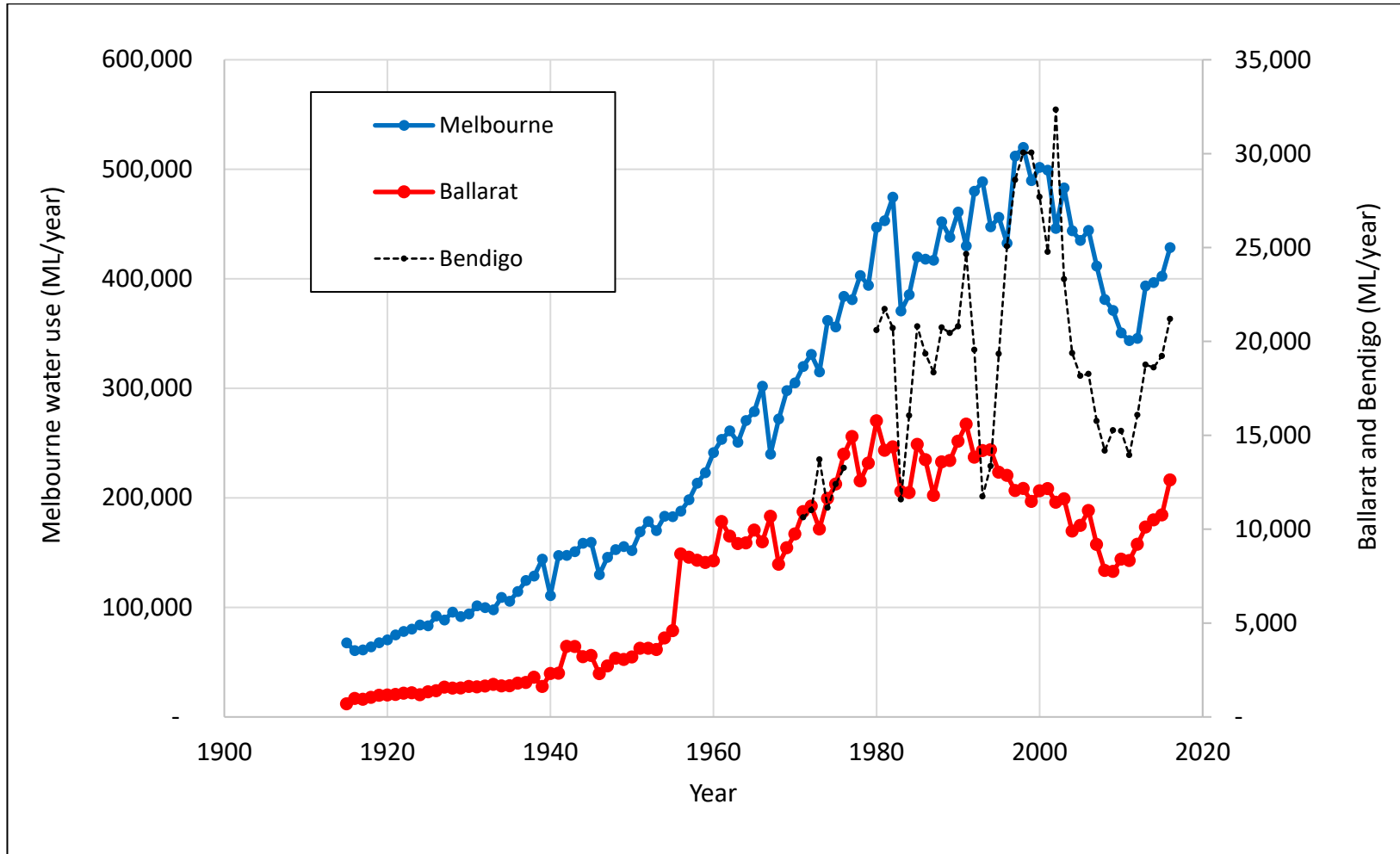


Figure 6.6 - Annual water use in Melbourne, Ballarat and Bendigo

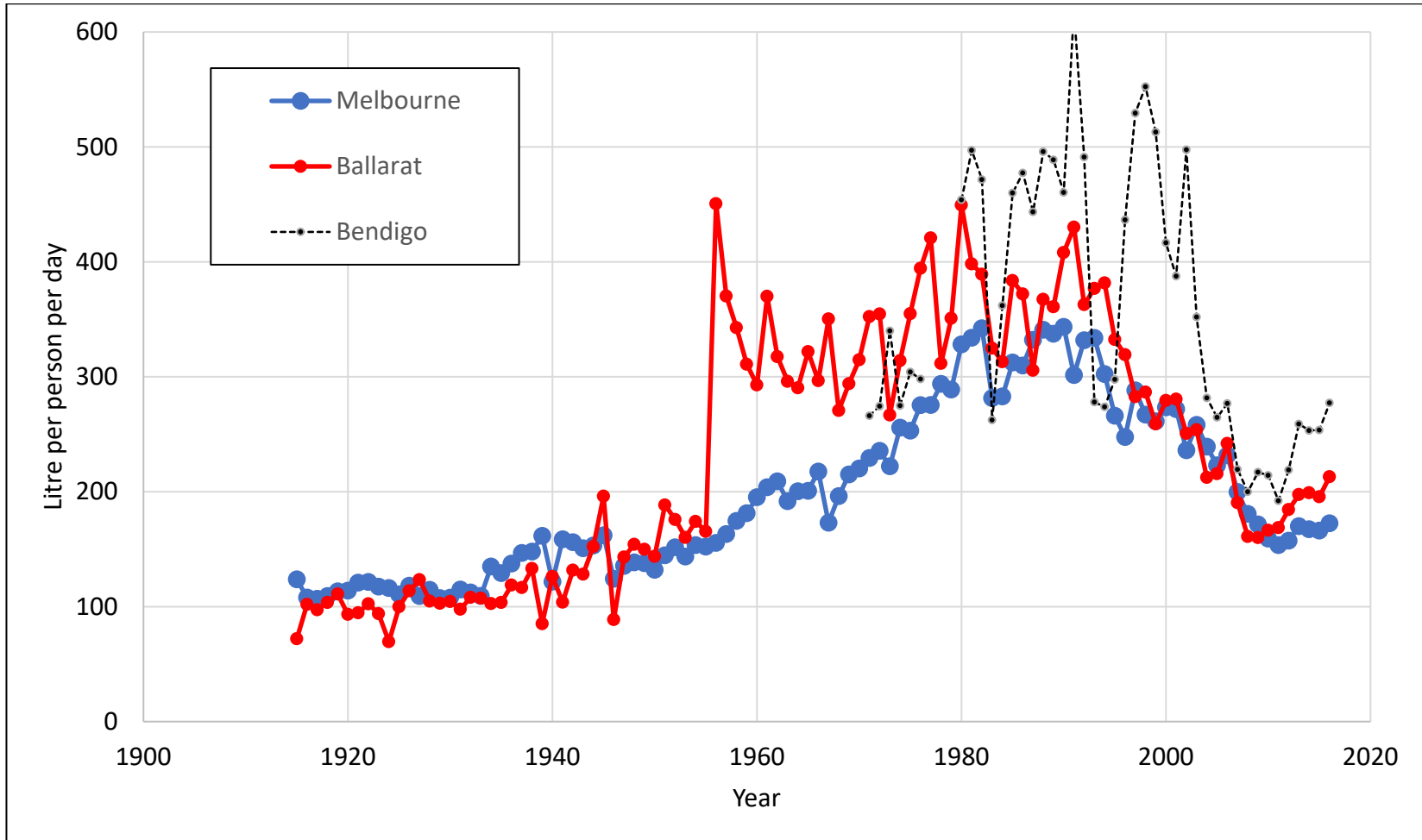


Figure 6.7 - Annual per capita water use in Melbourne, Ballarat and Bendigo

6.8.1.1 Drivers of water use

Due to the water pricing in Bendigo with irrigation, domestic and commercial tariffs creating additional complexity, the price for domestic water could not be determined historically from the data available. The comparison is therefore between Melbourne and Ballarat.

The results for Melbourne shown in Figure 6.8 are presented in the same format as those for Ballarat in Figure 5.4, with CPI adjustments having been made using 2015 as the base. While there are some similarities in trends, there are also significant differences.

While water use increased in both cities until 1980, in Melbourne this did not result in continually decreasing prices. The price of water was either maintained in real terms or increased. This resulted in the price of water in Melbourne in 1980 being twice that for Ballarat.

Price rises occurred in Melbourne from 1980 to 2008, but not to the same extent as in Ballarat. While the price in Ballarat increased almost four fold in real terms, in Melbourne the increase was no more than 50%. Perhaps unsurprisingly, the strong relationship between price increase and reduced demand is not seen in Melbourne over this period.

More recent price increases however have shown an identical relationship, with no further decreases in consumption. This is another clear demonstration of the limitations of price as a control mechanism once discretionary water use has been minimised. Over this time, the increases in Melbourne have been greater than in Ballarat, with current domestic water prices being similar in both places.

The change in discretionary and non-discretionary use is very similar in both cities (Figure 6.9). The decreasing trend of sewer flow as a percentage of water supply indicates increasing external water use in both places which was reversed, driving down the overall uses as discussed, with both cities appearing to settle with approximately 80% of water use now occurring indoors.

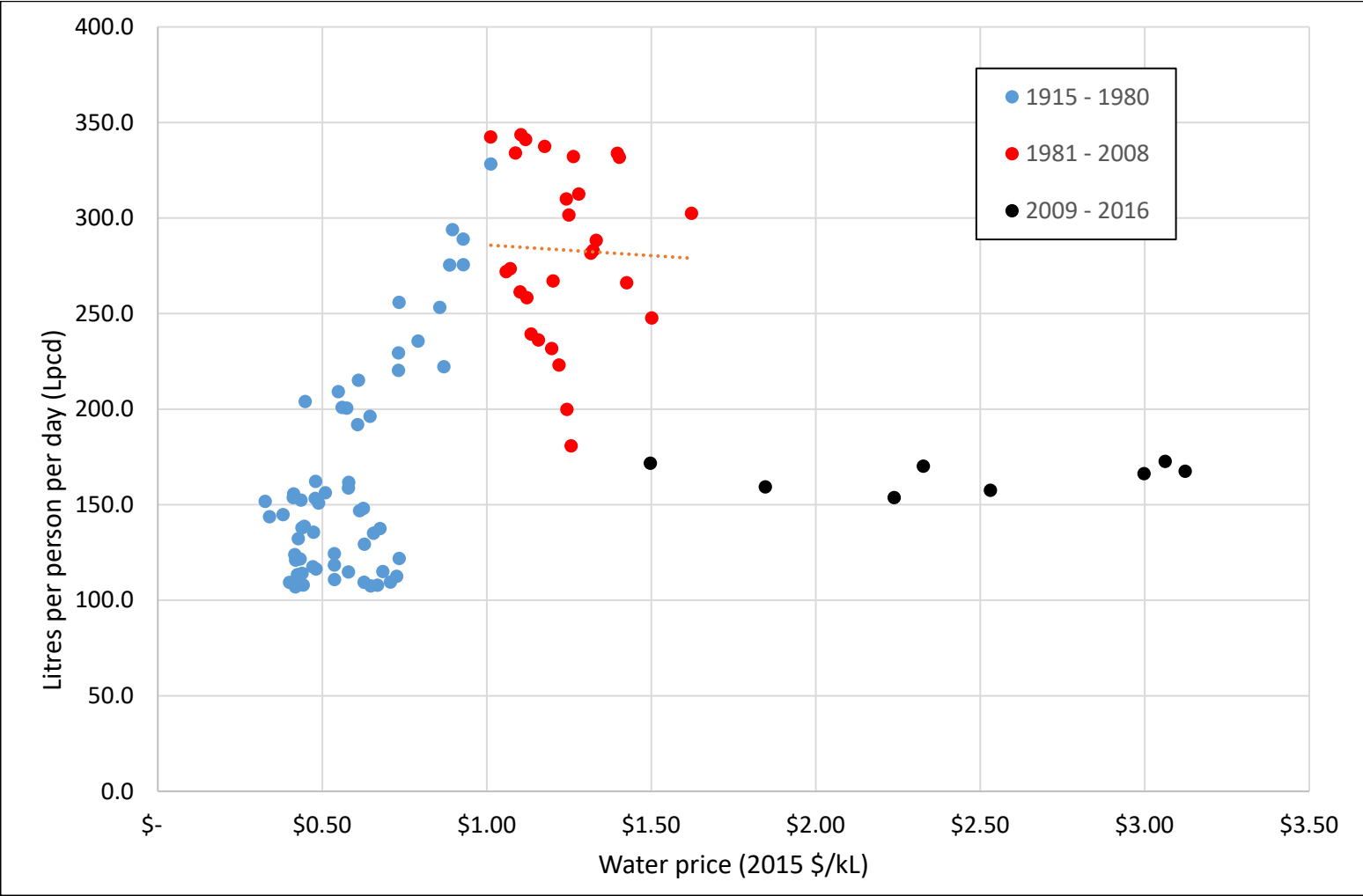


Figure 6.8 - Melbourne per capita water use versus water price

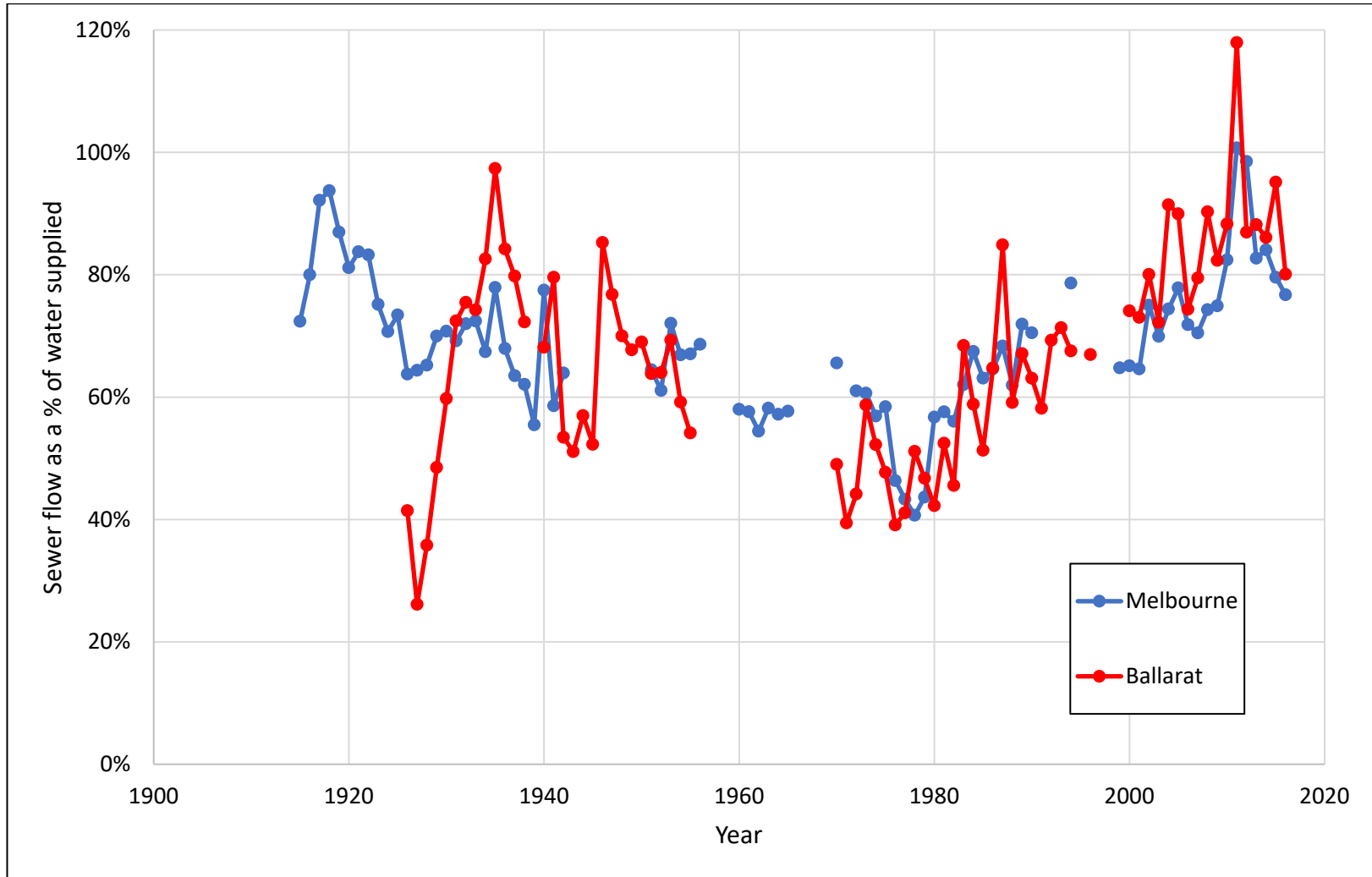


Figure 6.9 - Melbourne and Ballarat sewer flow as a percentage of water supply

6.8.2 River flow

6.8.2.1 Bendigo

Two streams within Bendigo have been monitored, however one of these, Axe Creek, is a small (34 km²) rural catchment not considered comparable. The most similar to the Ballarat monitoring is Bendigo Creek, approximately 10km downstream of Bendigo with a catchment area of 203km². Monitoring is available for this from 1979 – 1991 and again from 1999, enabling some comparison of urban river flow pre and post drought, however given the inadequacies of other data available, a complete analysis of the causes of river variation has not been possible.

Bendigo Creek has a similar annual flow magnitude to the Yarrowee River in the post 1999 period (Figure 6.10), and also shows a decrease in flow from the earlier period, however this reduction is much less than that experienced in Ballarat.

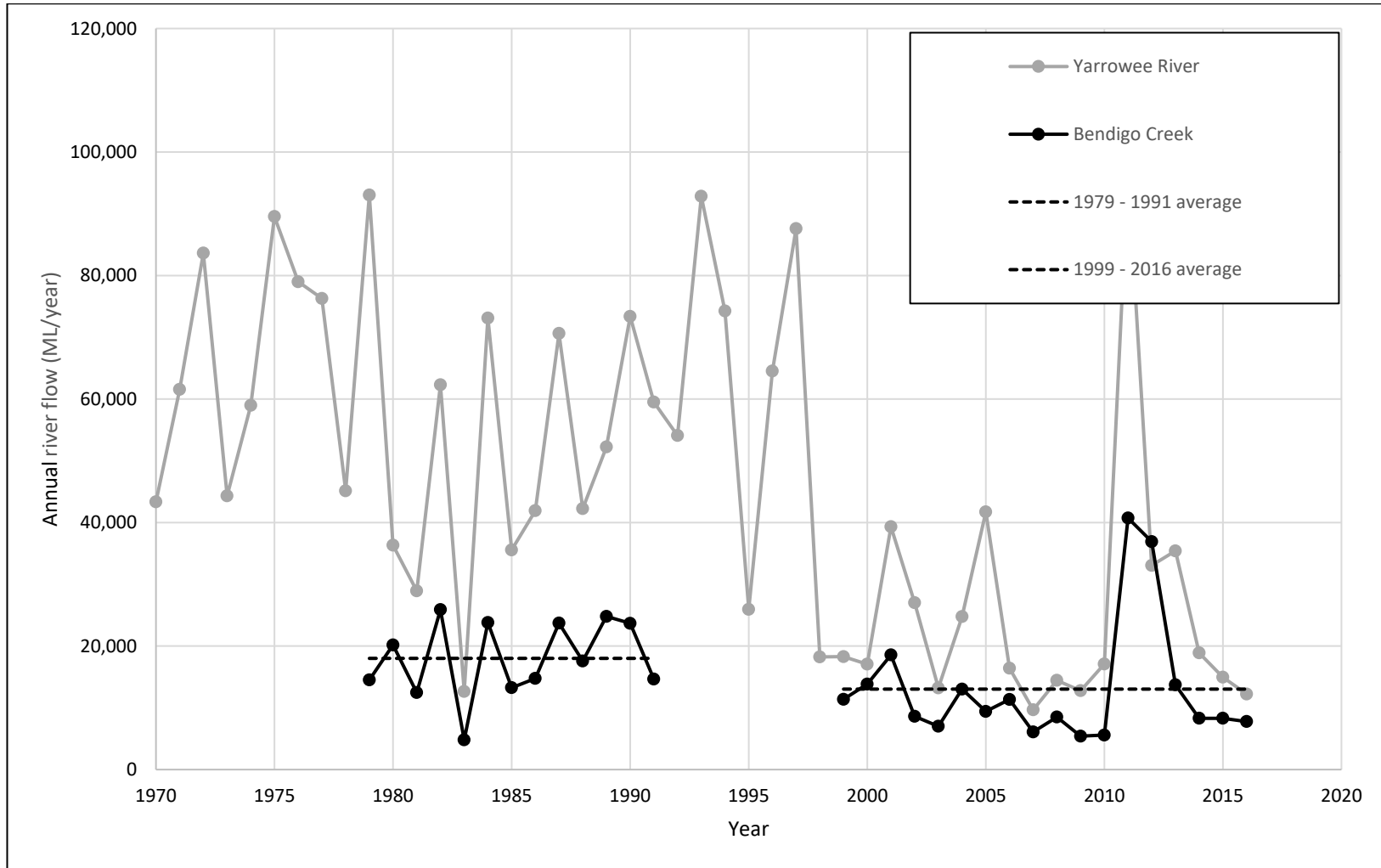


Figure 6.10 - Yarrowee River and Bendigo Creek annual flow

6.8.2.2 Melbourne

Urban population, population density and growth rate of Melbourne are all much higher than Ballarat, and more comparable to the large cities of the world. Therefore, any replication of the impact on river flows in Melbourne would be significant for the findings of Ballarat.

There are two major river catchments within the Melbourne urban area – the Maribyrnong and Yarra Rivers, and a number of smaller catchments. The gauging station on the Maribyrnong River within the urban centre is affected by tides and therefore not suitable for monitoring.

The Yarra River has four gauging stations between Warrandyte (rural or urban fringe) and Fairfield (urban), with gauges further downstream also affected by tides.

The Merri Creek gauging station at Craigieburn is on a small stream that has been significantly impacted by urbanisation. It is of similar magnitude to Bendigo Creek, however the reduction in flow is even more dramatic, with the 1977 – 1996 average flow of 12,000 ML/year reducing to 4,000 ML/year from 1997 – 2017 (Figure 6.11), despite the urban growth, in a manner similar to that for the Yarrowee River in Ballarat.

The Yarra River is a significantly larger river, the headwaters of which are used as part of Melbourne's water supply which must be considered when assessing the overall river flow, which also shows a significant reduction between pre-1997 and post-1997 annual average flows of 570,000 ML/year to 340,000 ML/year (Figure 6.12). However, the annual Melbourne water use has not increased over the past twenty years.

While extractions may have impacted the overall river, all the impacts will be recorded by the gauging station at Warrandyte. Therefore the difference in flows between gauging stations is of significant interest when assessing the impact of urbanisation on total river flow and the amount of water potentially available.

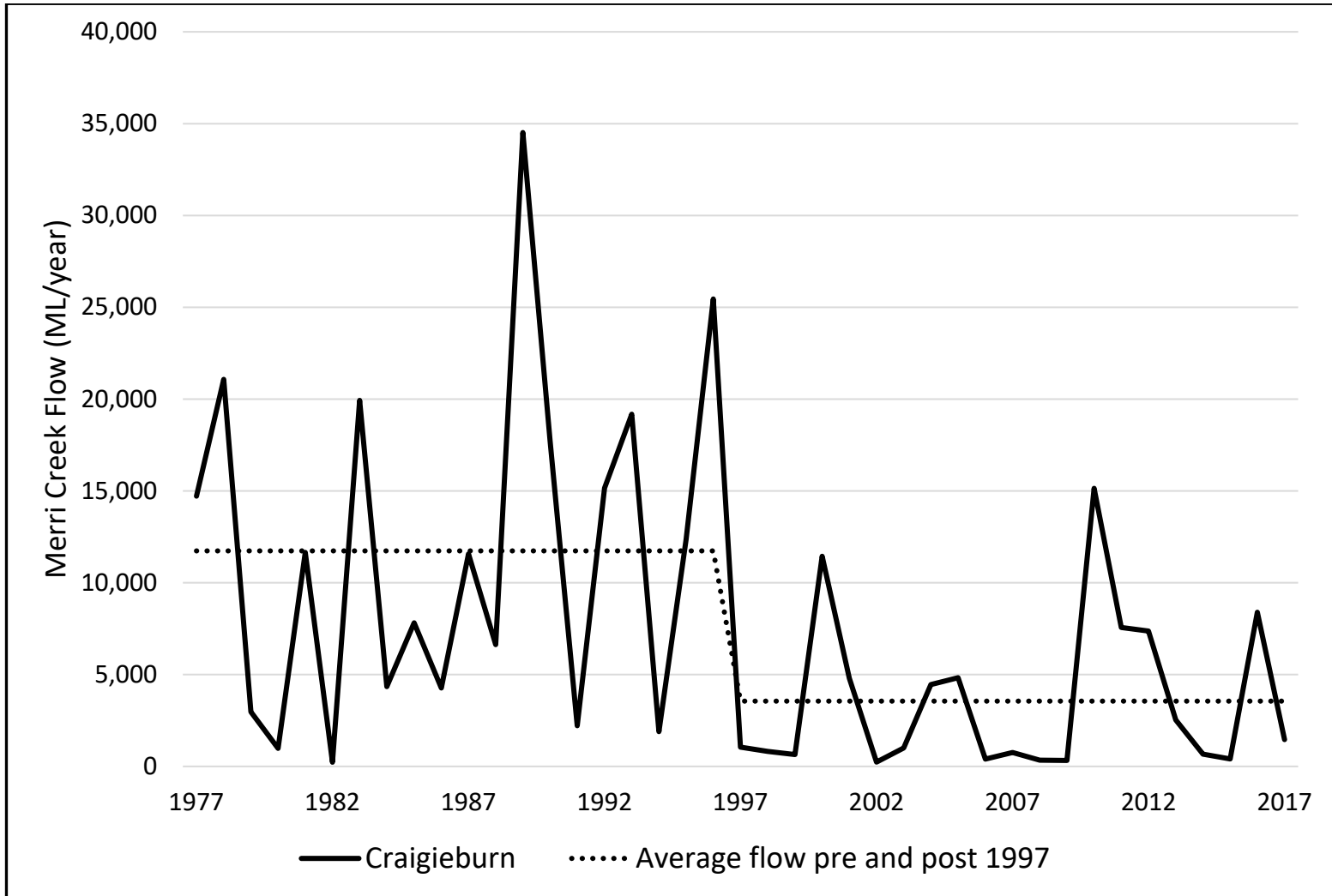


Figure 6.11 - Merri Creek annual flow at Craigieburn

The area between Warrandyte and Templestowe is outer suburbia, urban fringe and peri-urban development. The flow gauging indicates there is no significant change in the difference between the river flow in these two locations (Figure 6.13), with a slightly decreasing trend which may be consistent with the effect of the peri-urban development impacts around Ballarat.

Templestowe to Fairfield is within the urban boundary of Melbourne which has undergone significant development and densification over the past forty years. The increase in river flow is now 50,000 ML/year greater in Fairfield than forty years ago (Figure 6.14) an effect that could be contributed to the higher impervious paving. This is comparable to the 10,000 ML/year increase that was calculated for the Yarrowee River, in a portion of the city that is ten times the population of Ballarat with higher urban density, confirming both the calculation made regarding the increase in flow due to impervious area and that this has been more than counteracted by other changes in the runoff from the catchment.

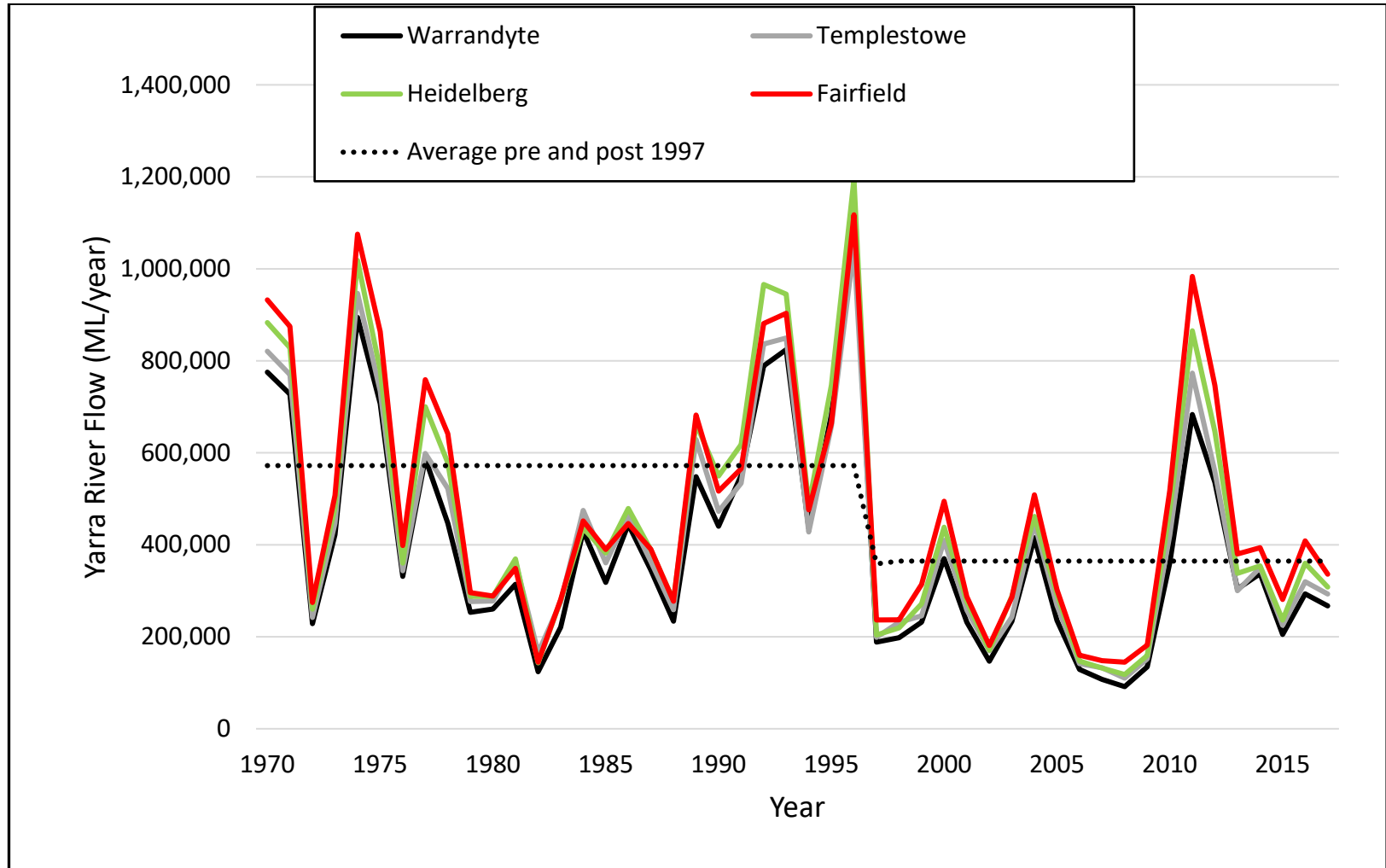


Figure 6.12 - Yarra River annual flow at four locations

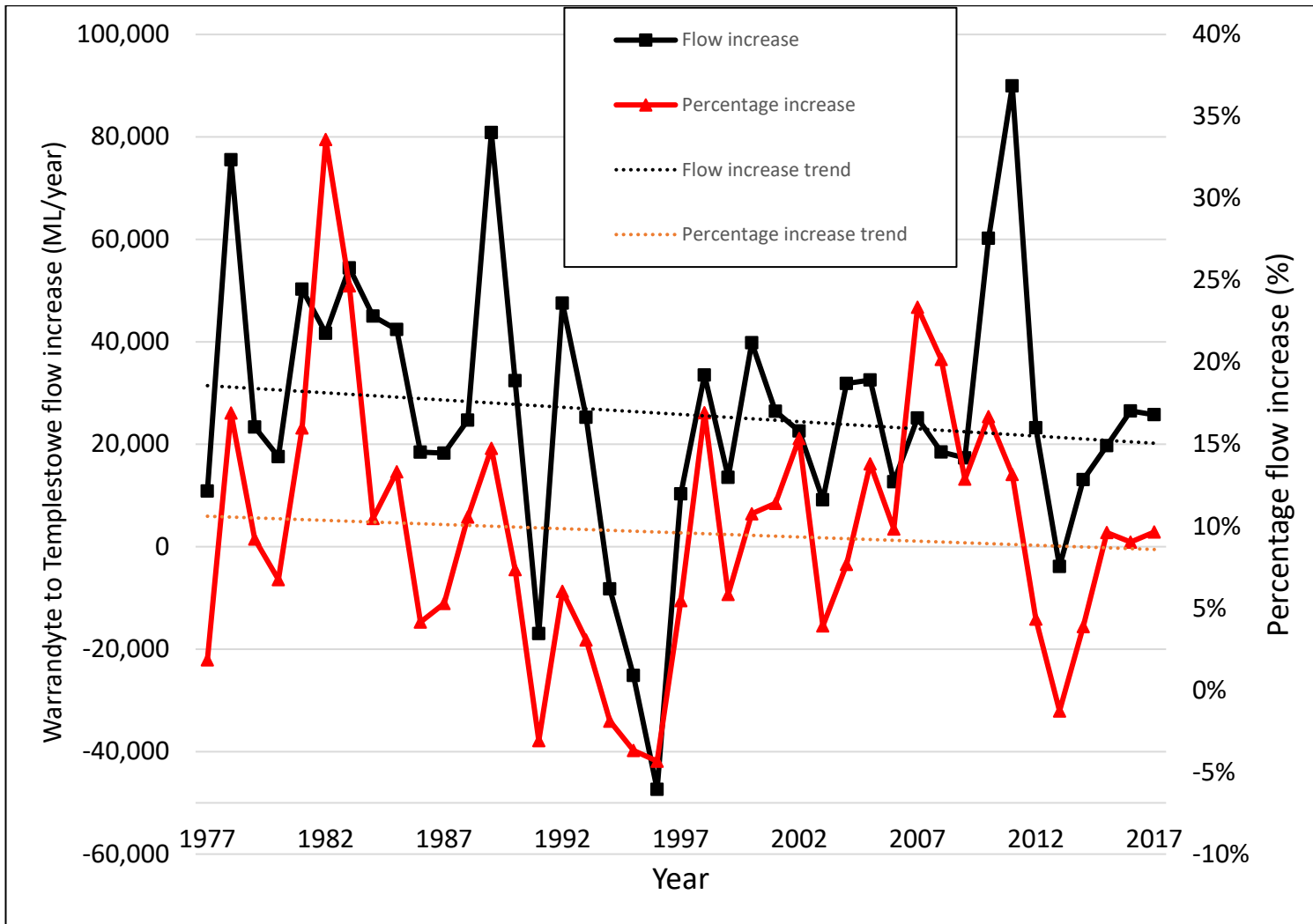


Figure 6.13 - Difference in Yarra River annual flow at Warrandyte and Templestowe

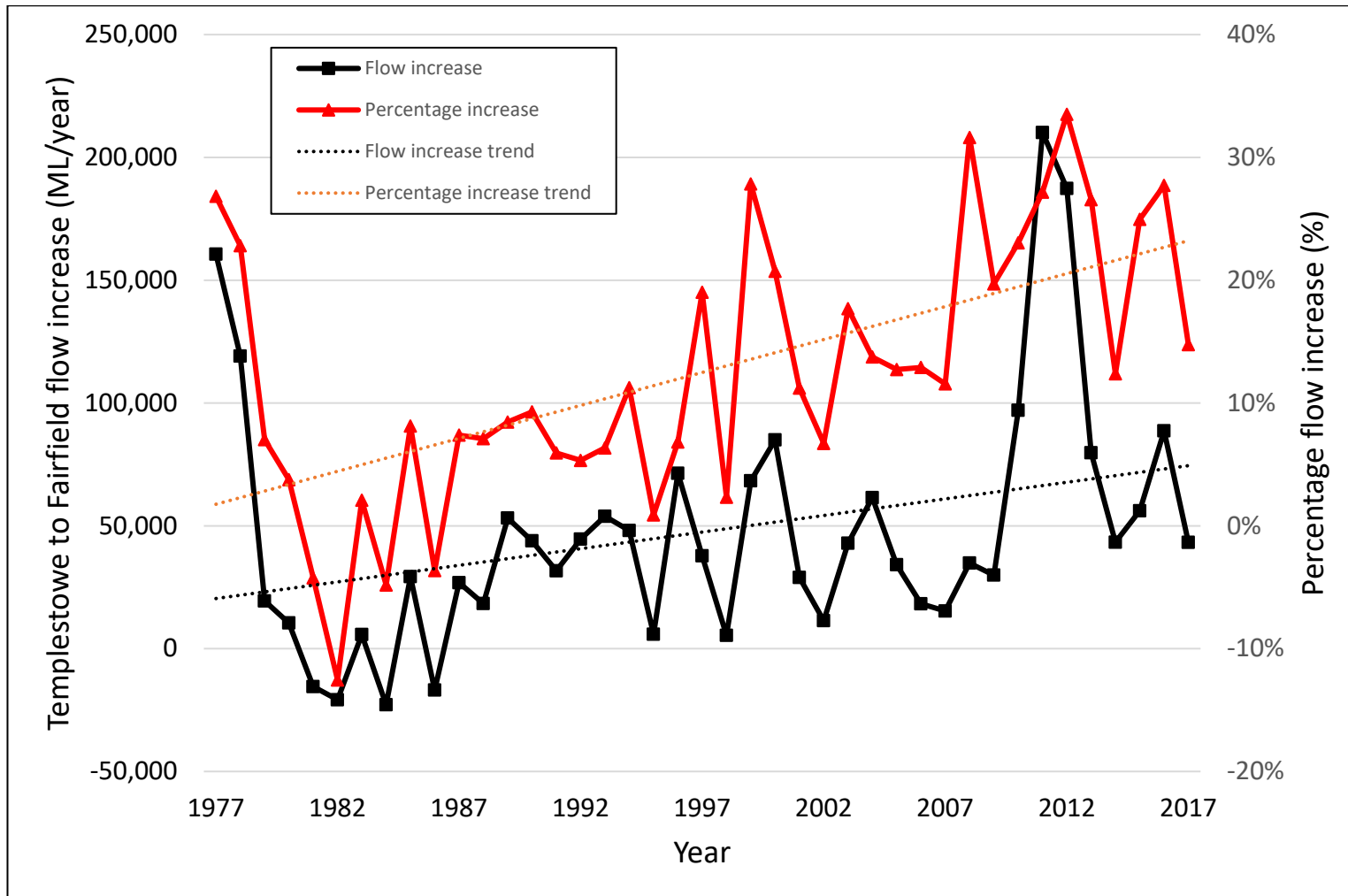


Figure 6.14 - Difference in Yarra River annual flow at Templestowe and Fairfield

6.8.3 Conclusions

Data from Bendigo, a city similar in size to Ballarat, and Melbourne, a city fifty times the size, confirm the results from Ballarat regarding water use and downstream flow.

Water use per person in Melbourne and Bendigo did not significantly increase between 1980 and 2000 similarly to Ballarat, a period before the introduction of long term restrictions due to the Millennium Drought, supporting the conclusion that long term consumption reductions can be achieved.

While the Melbourne data is not such a clear example as Ballarat regarding the impact of price on consumption, it again clearly shows that price increases produce no reduction in non-discretionary, inside water use.

Flow downstream of the city has reduced in both Melbourne and Ballarat during periods of urban growth due to other factors, despite an increase in flow due to the impervious areas. The increase in flow over time due to impervious surfaces in Melbourne over time is consistent with the results for Ballarat.

Flow monitoring downstream of a city can be a key element in assessing the success of IUWM, and additional monitoring or accessibility of information may be required if unintended consequences are to be avoided.

7. UNDERSTANDING URBAN GROUNDWATER BASEFLOW: piecing together hydrogeologic change through the historical development of a city

The change in groundwater baseflow has been clearly shown in the Ballarat results (Figure 6.4), however the impact of urbanisation on groundwater and the interaction with surface water is not well understood. Developing a greater understanding of the changes in groundwater around Ballarat can assist this.

While the aquifers and geology around Ballarat is well known, the groundwater flow into the Yarrowee River has not been investigated in academic literature. Long-term groundwater monitoring has occurred spasmodically within the Yarrowee River catchment, but data has not been collected for the purpose of understanding river baseflow. The Yarrowee River catchment does not contain aquifers used for irrigation with groundwater, but there has been exploitation for stock and domestic purposes. The legacy data available from a variety of sources, including those outside of the science domain, is used to establish an understanding of the groundwater and the impacts of urbanisation around Ballarat. While results from this type of study would not be adequate for a detailed quantitative study, they can provide insights without the requirement of expensive groundwater investigations.

Initial results from this work have been presented at the HWRS conference in December 2018 (David Ebbs *et al.*, 2018) and a manuscript, as presented in Chapter 7, has been submitted to a peer reviewed international Journal Environmental Earth Systems (Ebbs *et al.*, 2019).

7.1 Abstract

Urbanisation and the resulting increased imperviousness of catchments affects both surface and groundwater hydrology. The influence on groundwater is complex with changes to infiltration and extraction resulting from development within the regolith including irrigation, sub-surface drainage, stormwater management, leaking pipes and waste water discharge. Almost all cities have qualitative data that can be used to glean an insight into the hydrological changes throughout their urban expansion. This paper demonstrates by applying the principles of hydrogeological science to historical and empirical observations such as accounts of historic settlement, mining records, bore construction records and some groundwater monitoring, a greater understanding and a likely answer to the question of changes to water tables within aquifers and baseflow of a river can be reached, and links made to the degree of urbanisation. The need for understanding the impact of urbanisation on groundwater systems is widely recognised and the use of historic and legacy data can enable understanding to be gained that would otherwise not be possible without a long period of groundwater monitoring.

7.2 Introduction

Urbanisation and the resulting increased imperviousness of catchments affects both surface and groundwater hydrology. Increasing peak runoff and the resulting waterway impacts are widely recognised (Fletcher *et al.*, 2012; Shuster *et al.*, 2005) and have been a motivation for the development of Water Sensitive Urban Design (WSUD) techniques (Lloyd, 2001; Wong, 2006). The effect on total stream flow is contextual and dependent on many factors including climatic conditions, transfers and extractions, change in evapotranspiration, surface storage, consumption and waste water discharge. While the idea that total runoff increases with greater imperviousness has long been considered (Jones, 1971), there has also been recognition that this is not universal (Fletcher *et al.*, 2007). As an example, recent analysis of historical data has demonstrated that the increased urbanisation of Ballarat, a provincial city in Victoria, Australia, over a 60 year period did not result in increased stream runoff, but rather reductions in total flow due to climate, additional farm dams, installation of rainwater tanks and a reduction in baseflow (D. Ebbs *et al.*, 2018d).

The influence of urbanisation on groundwater is complex (Howard, 2002), with changes to infiltration and extraction resulting from development within the regolith including irrigation, sub-surface drainage, stormwater management, leaking pipes and waste water discharge (Foster, 2001). Some of the major effects are recognised as changes in groundwater quality and changes to stream baseflow (Bhaskar *et al.*, 2016; Schirmer *et al.*, 2013), but the complexity and lack of data often makes the quantification of this difficult (Han *et al.*, 2017).

Groundwater investigations can be expensive, and once established, monitoring may not be continued as requirements and priorities change.

Nevertheless, almost all cities have qualitative data such as local history and administrative documents that can be used to glean an insight into the hydrological changes throughout their urban expansion. Sources include maps, diaries, letters and accounts written by explorers and early settlers, depictions of early landscapes in art work and photography, and historical descriptions of water holes, wells, ponds and lakes and the conditions faced during development. These descriptions will rarely give quantitative data on groundwater levels, however the qualitative data can be compared to current conditions to give an indicative sense of change.

Council records, local building regulations and reports on infrastructure development can provide information regarding difficulties with foundations, problems associated with installation of below ground infrastructure or the expected issues from groundwater interaction. Where mining has been a significant component of a region's economy, exploration records regarding the viability of development may be available and provide watertable height and quantity of water and pumping requirements. Anecdotal evidence of groundwater trends can be obtained from media reports such as springs, seeps and bores drying up, subsidence, sink holes, road damage, salinity or other issues that may be associated with rising or falling groundwater tables. The list provided here is indicative rather than comprehensive, and the process usually requires searching through copious records for indirect references to groundwater information or data. However, quantitative information more directly related to groundwater may be gleaned from previous hydrogeological investigations for any purpose, such as agricultural, contamination or salinity studies, and geological maps provide the required conceptual model of a region's hydrogeology and where groundwater baseflow to a river may be derived.

In Australia, as in many jurisdictions, a license is required to construct a bore for groundwater purposes and these records usually indicate depth and yield, in addition to location and frequency. In areas where groundwater use is common, groundwater monitoring records are usually available.

Such evidence drawn from outside of the traditional science domain can inform hydrological science, even challenging paradigms (Dahlhaus *et al.*, 2008; Dahlhaus *et al.*, 2010). This paper presents an example where a diverse range of legacy data sources are used to provide information on the changes to groundwater systems around the expanding city of Ballarat. The study demonstrates that while a lack of traditional scientific data may not enable detailed quantitative analysis, a deeper understanding of the changing urban hydrology can still be gained. It challenges the notion of what constitutes groundwater data

and shows that by applying the principles of hydrogeological science to historical and empirical observations, a definitive answer to the question of the impacts of aquifer water tables on groundwater baseflow can be reached, and links made to the urbanisation of this aquifer.

7.2.1 Landscape setting

Ballarat is a city in south eastern Australia (37.5622° S, 143.8503° E) of 103,964 inhabitants in 2016 (Australian Bureau of Statistics, 2017). The surrounding area was historically sparsely inhabited by indigenous Wathaurong (Wadda Warrung) people. The first settlement by European people was in 1837, but the location of the city was predominantly determined by the discovery of gold in 1851 (Victorian Government, 1857). Located at the intersection of five surface water catchments, the majority of the city's drainage is via the Yarrowee River, a tributary of the Leigh River, which in turn feeds the Barwon River. The catchment area of interest (Figure 1a) is defined as the 593 km² upstream of the stream flow gauging station at Mt Mercer, approximately 29 km south of Ballarat, immediately downstream of the junction of the Yarrowee River and Williamson's Creek, at which point the waterway becomes the Leigh River. The gauging station (No. 233215) is part of the river gauging network overseen by the Victorian Department of Environment, Land, Water and Planning and has data records back to 1957.

Within this catchment there are four main aquifer systems, shown in plan view (Figure 1b) from information from the Geological Survey of Victoria, and the aquifer diagram showing typical arrangement and depths (Figure 1c) adapted from SKM (2012):

1. Basement Aquifer comprising Palaeozoic bedrock made up of sedimentary and metamorphic rocks of Ordovician age (slate, shale, sandstones) and granitic rocks of Devonian age. The basement aquifer has low hydraulic conductivity values, typically measured as microns per day (Crozier & Broome, 1995), is low yielding, and the groundwater salinity is generally higher than 3,000 mg/L total dissolved salts (TDS) (Dahlhaus *et al.*, 2002), hence it is not widely exploited for water supplies.
2. Upper Tertiary Aquifer comprising fluvial sediments (consolidated gravels, sands, silts, clays), known as 'deep leads', representing ancient river valleys buried by volcanic rocks or post-volcanic sediments. The deep leads are widely variable in their permeability, yield and water quality and are not widely exploited, largely due to their depth and limited extent.
3. Basalt Aquifer comprising volcanic rocks of Neogene and Quaternary age (mostly basalt with some minor scoria). As a fractured rock aquifer, the basalts generally have higher

hydraulic conductivities and yields, although they are spatially variable. Water quality varies from <1000 mg/L TDS (i.e. potable) to > 5,000 mg/L TDS. The basalts are the most heavily exploited of the four systems, with most water used for domestic and stock water in rural areas, and garden irrigation in urban areas.

4. Quaternary Aquifer, comprising a variety of sediments of alluvial, colluvial, lacustrine and paludal origins (weakly consolidated gravels, sands, silts, clays). Of limited extent and thickness, the groundwater quality is useful, but the yields are generally unsustainable for significant use. It is occasionally exploited for domestic uses, including garden and sports ground irrigation.

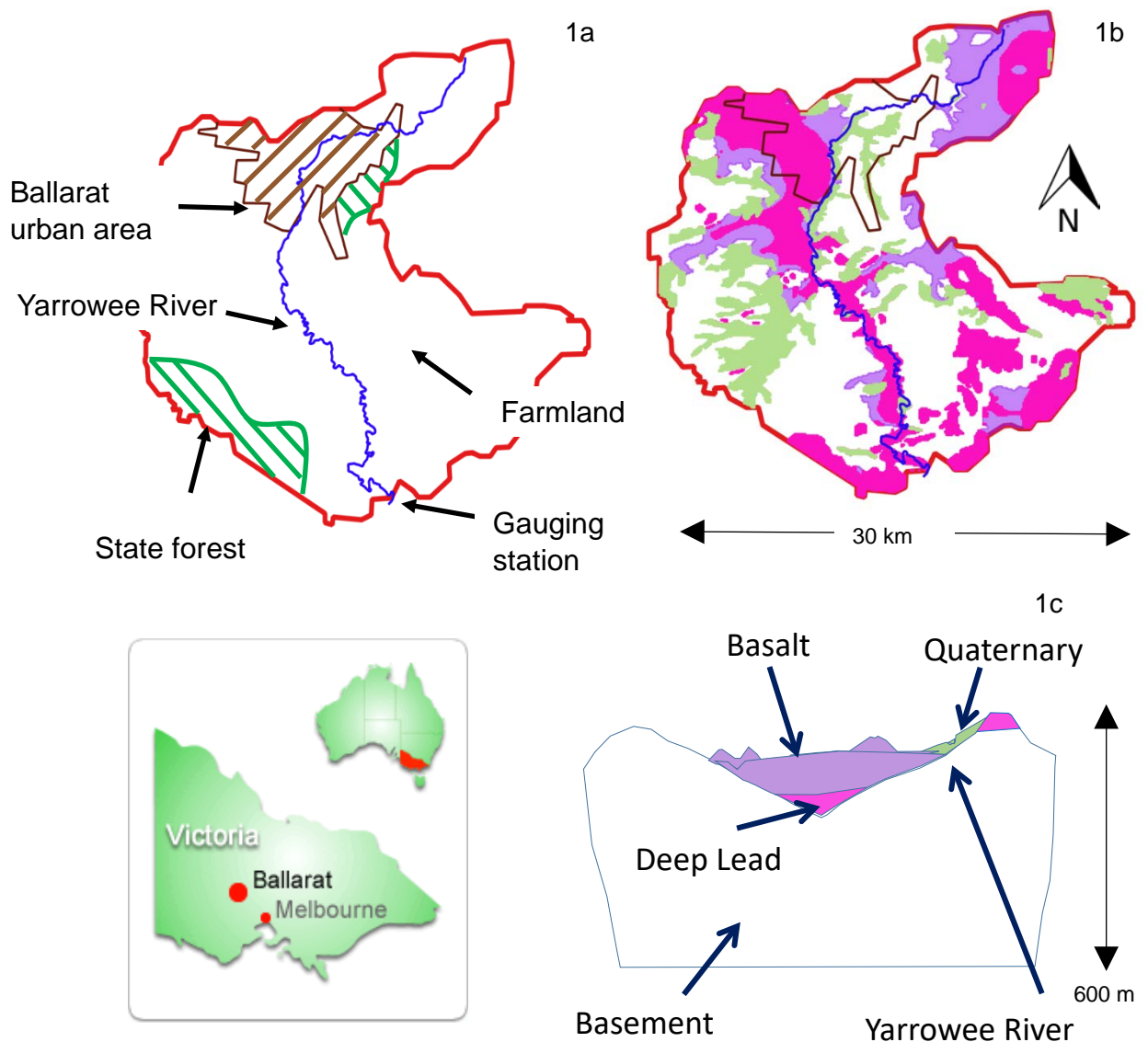


Figure 7.1: a) Yarrowee River catchment showing the Yarrowee River and an outline of the Ballarat urban area, b) the aquifer systems within the Yarrowee River catchment – basement (white), deep leads (pink), basalt (purple) and quaternary (green) and c) Aquifer relationship diagram adapted from (SKM, 2012)

Understanding the land use changes around Ballarat will assist in placing changes to groundwater into context. Little is recorded of the landscape changes in the study area made by the Wathaurong people, but it is generally inferred from the early ethnohistorical accounts that their impact on the natural environment was minimal (Nathan, 2007). At the time of settlement by European people the area was noted to be entirely forested (open grassy woodlands) by the initial visiting parties (Bonwick, 1858; Learmonth, 1853; Withers, 1887), as illustrated in artwork from the area at the time (Figure 2). The gold rush of the early 1850s resulted in rapid and widespread environmental change. Mining led to wide scale clearing as wood was required as fuel, and structural timber as reinforcing for

underground mining and city building materials. Major disturbance took place as any land with potential to yield gold was overturned.



Figure 7.2: Ballarat region as depicted by Eugene von Guerard prior to European settlement and mining (vonGuerard, 1854), and photographic evidence of the impact of mining (SLV, 1870)



Shallow diggings combined with sluice mining resulted in wide scale erosion and sediment flows in the Yarrowee River, something that was not overcome until 1910 (McBride, 1911). The 'Great Flood of Ballarat' in 1869 (Argus, 1869) highlighted the need for improved drainage and led to the channelisation of the Yarrowee River through the city centre, and was a justification of the establishment of the first reservoir upstream of the city (Central Highlands Water, 2016). After the initial gold rush associated with alluvial mining receded, deep lead mining and quartz reef mining with shafts hundreds of meters deep commenced, creating megapores throughout the aquifers at depth. The 'largest pumps in the colony' were

required for dewatering, and the closure of some mines resulted in the water infiltration in adjoining mines exceeding the pumping capacity (Brough Smyth, 1869).

The major mines in Ballarat had closed by the time of World War I (1914 – 1918), and the population stabilised until after World War II (1939 – 1945). Urban expansion has been continuous since then, with population growth, a reduction in residents per dwelling and increased home size resulting in a quadrupling of the paved area.

The masonry-lined stormwater channels replacing the Yarrowee River through the centre of the city remain the major source of drainage with more than 70% of the urban area discharging rainwater runoff via this stream. A separate black sewerage system was first installed in the 1920's, with the city fully connected by the 1970's, and 75% of the city's domestic sewage discharges into the Yarrowee River via a waste water treatment plant. Mining recommenced in Ballarat in the 1980's with a single underground commercial operation which continually discharges to the river from mine dewatering.

Groundwater (drawn from a deep lead aquifer and basalt aquifer to the west of Ballarat) was used to supplement the urban water supplies during the Millennium Drought (1999 – 2010) and trials of managed aquifer recharge (MAR) have been completed but there is no ongoing groundwater extraction by the water supply authority. Groundwater bores for stock and domestic supplies are in seasonal use.

Previous work on the impact of urbanisation on the Yarrowee River includes an annual water balance over sixty years for the river (D. Ebbs *et al.*, 2018d). This accounted for all transfers into and out of the catchment (CHW, 2016), urban water consumption, treated sewage discharge and dewatering flows from Ballarat Goldfields producing the runoff due to rainfall and the hydrologic response of the catchment. Comparison with expected runoff due to climatic variations enabled quantifiable impacts of urbanisation on the river to be attributed. This work also demonstrated that dry weather flow of the river excluding discharge from the Waste Water Treatment Plant, had significantly reduced over the time of monitoring. The baseflow contributed by groundwater was considered to be the river flow on the 4,088 days where there had been four or more days with no rain, with the contribution from the sewage treatment plant removed. While on average the sewage treatment discharge is approximately 10% of the river flow (with mine dewatering being less than 1%), during the summer period the river now relies on this entirely. During ten of the past twenty years there was no groundwater baseflow (Figure 3), something which had previously only occurred once during the investigation period, in the 1967 drought, a change that is statistically significant at a 99% Confidence Interval. Correlating this change to baseflow with changes in groundwater will assist in identifying significant impacts of urbanisation on the groundwater within the Ballarat region.

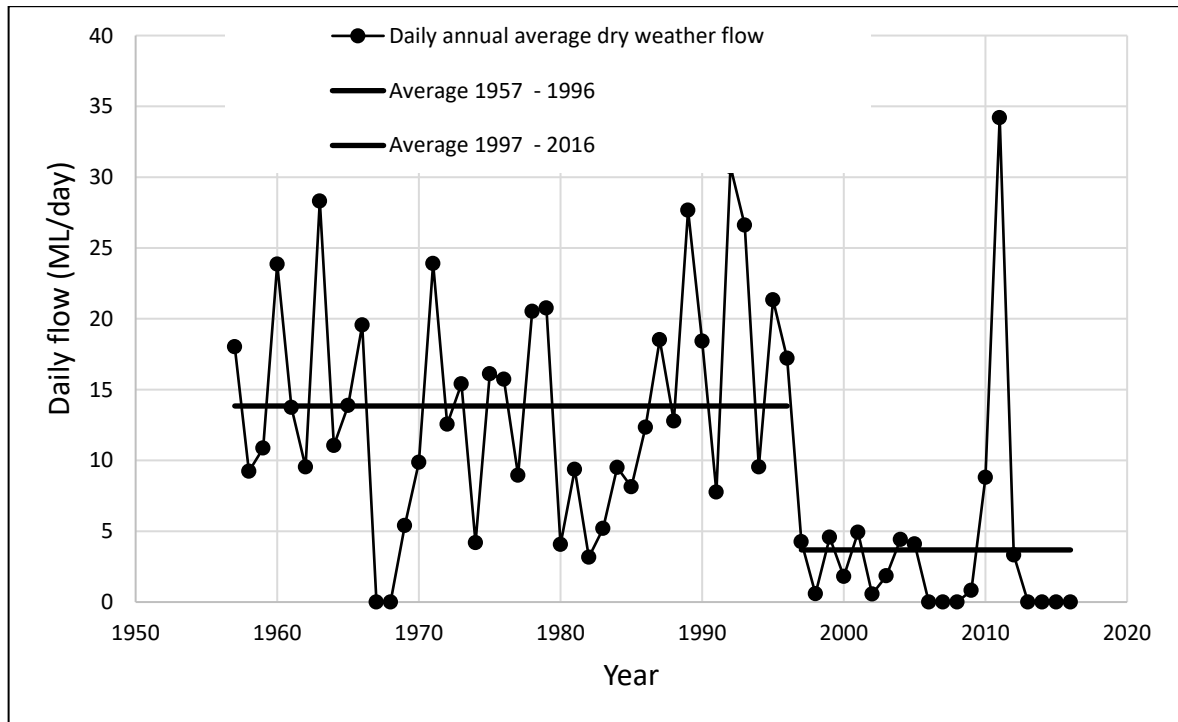


Figure 7.3: Baseflow of the Yarrowee River excluding sewage treatment plant discharge

7.2.2 Data sources

In this project, a variety of historical records were used to establish indicative groundwater levels at the time of European settlement. The early history of Ballarat (Withers, 1887) has observations on water levels from early settlers prior to the discovery of gold. There are extensive records during the mining period (Baragwanath, 1923; Brough Smyth, 1869) including water levels within mines and their location which provided an understanding of the groundwater levels within the different aquifers.

The depth of the watertable recorded when bores are drilled, referenced to Australian Height Datum (AHD), has been used to indicate change over time within each aquifer. Where one aquifer overlies another, the depth of bore is assessed against the known aquifer depth at that point to determine the data set in which it belongs. Data sourced through the Visualising Victoria's Groundwater (VVG) internet portal (Dahlhaus *et al.*, 2016; Federation University Australia, 2018) identified 1533 bore sites drilled within the catchment boundary for various purposes including stock and domestic use, groundwater investigation, monitoring and observation of which 389 have bore depth recorded, although no commercial or irrigation bores were found. The standing water level at the time of construction is not available from the information sourced through the VVG, but was obtained from archived information from the Victorian Groundwater Management System (DEPI, 2013). The earliest record is from

the 1950's with only a few scattered results from early years and regular information on bore construction commencing with the introduction of the *Groundwater Act 1969*.

There is significant overlap of the Basalt Aquifer with the deep lead, where the volcanic lava streams flowed through the ancient river systems, so they cannot be distinguished in two dimensions. The Victorian Aquifers Framework supplies the spatial map of the upper and lower limits of each aquifer, and the depth of the groundwater bore then determines whether the water is extracted from the basalt or the aquifers below. For groundwater bores located in the basalt aquifer, data displayed was restricted to only those bores adjacent to the Yarrowee River and most likely to affect baseflow, which are immediately to the west of Ballarat (Figure 4a). Trends within other expanses of basaltic rocks remote from the river, although potentially connected via groundwater or tributaries, have not been shown as they provide similar information while the differences in elevation clutters the figures.

In addition to the bores with information at the time of construction, 17 bores were identified with regular water level monitoring data over varying periods of time, and this data is available from the Victorian Government Water Measurement Information System (DELWP, n.d.-d). This regular monitoring data has been used to compare with and confirm the information from bore construction records. Bore construction licences, extraction permits and metered use has been obtained from the company vested with the licensing, Southern Rural Water (SRW).

Groundwater level is influenced by the catchment water balance and whether there is an import or export of water. The ratio of stream discharge to basin recharge can be used to indicate whether a catchment is a groundwater importer or exporter (Schaller & Fan, 2009). Rainfall on the catchment is available from four different stations from 1880 (BOM, n.d.) with a spatial average used to calculate catchment rainfall. A water balance to determine stream flow excluding additions and extractions has previously been completed for the Yarrowee River (D. Ebbs *et al.*, 2018d), and this has been compared with the recharge rate calculated from data accessed from the Bureau of Meteorology (Hafeez *et al.*, 2015) for the period 1957 - 2017.

7.2.3 Watertable Ratio

In many cases the watertable is a subdued replica of the aquifer topography, but this is not always the case. It has been shown that the watertable of an aquifer can be classified as two distinct types – recharge or topography controlled (Haitjema & Mitchell-Bruker, 2005). To determine this, three dimensionless parameters are used:

$$\frac{L}{H} = \text{Ratio of aquifer width to aquifer height} \quad (1)$$

$$\frac{L}{d} = \text{Ratio of aquifer width to maximum terrain rise} \quad (2)$$

$$\frac{R}{k} = \text{Ratio of recharge rate to hydraulic conductivity} \quad (3)$$

The product of these, termed the Watertable Ratio (WTR) (Gleeson *et al.*, 2011) gives the equation for the 'rule of thumb' which indicates if an aquifer is recharge or topography controlled, if:

$$WTR = \left(\frac{L}{H}\right) \times \left(\frac{L}{d}\right) \times \left(\frac{R}{k}\right) < 1 \text{ then recharge controlled}$$

$$WTR = \left(\frac{L}{H}\right) \times \left(\frac{L}{d}\right) \times \left(\frac{R}{k}\right) > 1 \text{ then topography controlled}$$

The aquifer width and height and the terrain rise (L,H and d) were available from the spatial layers of the aquifers (Victorian Government, n.d.-b) and calculated using a standard geographic information systems (GIS) program. Estimates of the hydraulic conductivity (k) were obtained from assessments of the groundwater systems within the region (Dahlhaus *et al.*, 2002), while the recharge rate is that used previously. An indicative WTR for each of the aquifers which potentially provide baseflow to the Yarrowee River is calculated to confirm the conclusions about aquifer performance drawn from observed data.

The historical observations about groundwater, hydrogeological information, climate records, groundwater depth from bore construction records and the available monitoring bore data has been combined to establish a detailed picture of changes to groundwater depth for each aquifer. From this, it has been possible to determine which aquifer has been the most significant contributor to the groundwater baseflow of the Yarrowee River. While it is not possible to be definitive in a study of this type, Impacts of urbanisation on this aquifer have then been related to the observed changes in groundwater.

7.3 Results

The results of changes to the water table within each aquifer are presented separately so that a determination can be made as to their relative impact on the Yarrowee River baseflow, Hydrogeological information is described, followed by historical observations for that aquifer. Information regarding groundwater levels between the end of the mining period in 1914 and the early 1960's is scarce. From 1960 data on all the groundwater bores that have been

drilled becomes available and this quantitative data is then presented. The rainfall anomaly (Figure 5) shows the period of the Millennium Drought in Ballarat (1997- 2009) and this period has been highlighted on the other time series graphs for reference.

This data is presented for the Yarrowee catchment along with comparative data on the influence of topography or recharge rates on the watertable level within each aquifer.

7.3.1 Basalt Aquifer

As described earlier, the highly fractured basalt aquifer has high permeability and groundwater has been exploited for stock and domestic purposes. The depth of the basalt layer adjacent to the Ballarat residential area varies between 50 and 100m, while in the lower reaches of the Yarrowee River it reduces to between 25 and 50m. The relatively high number of bores within the basalt, more than half of all recorded sites within the Yarrowee River catchment, is an indicator of the attractiveness of this aquifer for potential water supply.

By 1856, mines were being sunk through the basalt into the deep leads, and the example of the Great Western Company is illustrative of the water issues involved. "In 1858 ...water was so heavy they had to stop the works and procure twelve-inch pumps. After sinking into the second rock.... they had to put in a fifteen inch pump. ...In 1862 at 340 feet, they drove 180 feet, but struck a drift and were swamped, with the water washing in sand that filled 100 feet of the shaft. After eight years of mining they were again swamped, and in 1866 resolved this by the biggest pump in the colonies, a 90 horsepower beam engine and 22 ½ inch pumps" (p471).

The records of discrete observations at the time of bore construction (shown as points on the chart) and the monitoring bores records (Figure 4b) indicate there is no significant trend in groundwater level within the basalt aquifer. The majority of the monitoring bores were observed during the Millennium Drought, and despite ten years of below average rainfall, no trends outside seasonal variation were recorded.

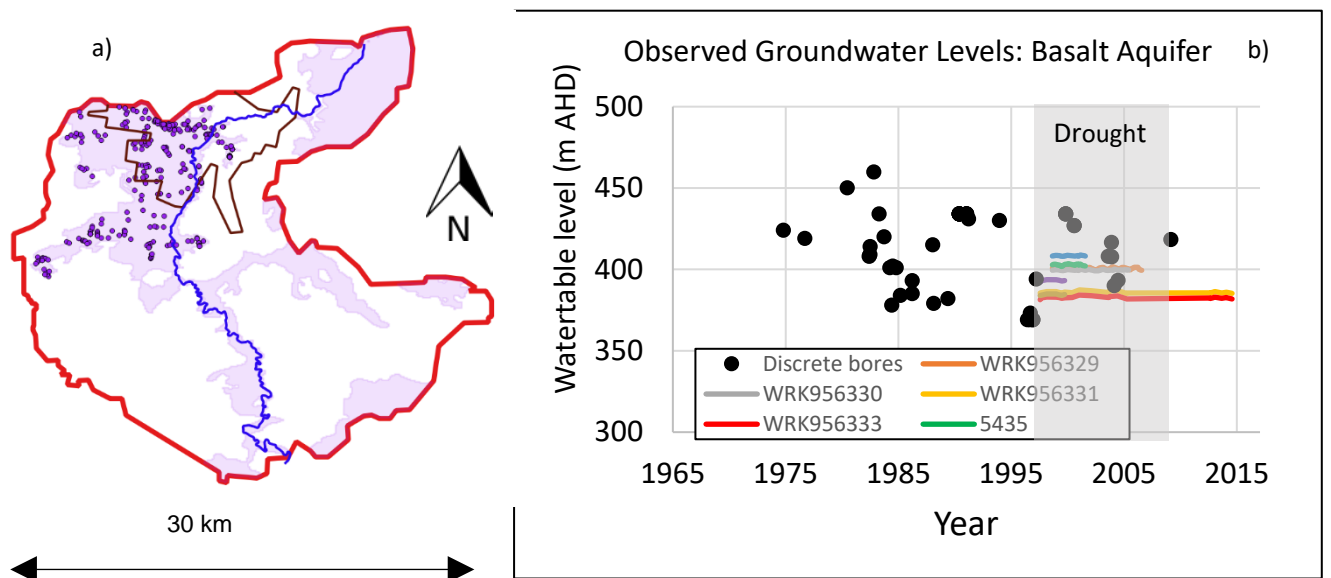


Figure 7.4: a) bores within Ballarat West basalt and b) groundwater level of discrete observations and monitored bores

Although there are observed seeps along the edge of the basalt which are providing some groundwater discharge to the Yarrowee River, the minimal baseflow recorded over the past 20 years indicates this is a relatively insignificant quantity. While there has been discussion in academic literature regarding the direction of flow within aquifers around Ballarat, there is general agreement regarding the separation between the surface water and groundwater divide (Branagan *et al.*, 2003; Taylor & Gentle, 2002) and within the central Ballarat urban area the groundwater in basalt may flow north while the surface water flows south. The thickness of the basalt results in the lower level of this aquifer being below the Yarrowee River, so flow through the full thickness of the basalt will not enter the river in this region.

The watertable in the basalt has been maintained during the driest phases within the monitoring period, which is consistent with the high permeability and recharge rates associated with this aquifer. The size of the basalt aquifer relative to the urban area of Ballarat suggests there has been minimal recharge impact from impervious surfaces. The maintenance of the watertable level at the time when groundwater baseflow to the Yarrowee River has significantly reduced indicates that the discharge from the basalt is not a significant source of river baseflow, and as the saturated thickness of the Basalt Aquifer is lower than the river bed level, it can be concluded that groundwater from the basalt must be discharging elsewhere.

7.3.2 Upper Tertiary Aquifer

Due to the depth, relatively low yields and the associated difficulties with extraction, the deep leads have rarely been exploited as a source of groundwater. The historical mining records indicate water issues with mining the deep leads was associated with traversing the basalt rather than the deep leads themselves. Only five bores constructed within the Upper Tertiary Aquifer were identified over the fifty years of record, inadequate data to give an indication of relative depth over time.

A monitoring bore (No 47192) within the Upper Tertiary Aquifer has collected data since 1987 (Figure 5a). The groundwater level is shown along with the rainfall anomaly, with the depth scale expanded compared with the results from the basalt (Figure 5b). The shape of the groundwater curve matches that of the rainfall anomaly with an immediate increase in level when the rainfall anomaly increases suggesting recharge being the controlling aspect.

The hydrogeology of the deep leads suggest both the amount of water stored and the transmissivity would be low. The low storage potential means that relatively large changes in watertable height may occur for given changes in volume, however, these may be localised or occur over a longer time period. The numerous shafts acting as macropores into the deep leads around Ballarat have significantly changed conditions, providing points of recharge that would not otherwise exist. Where these connect there may be impacts over a wider area, although on the catchment scale it is speculated that due to the geology, these changes are relatively localised. The strong correlation between the rainfall anomaly and the groundwater level within the monitored deep lead indicates that urbanisation has not had a dramatic impact on the amount of recharge occurring.

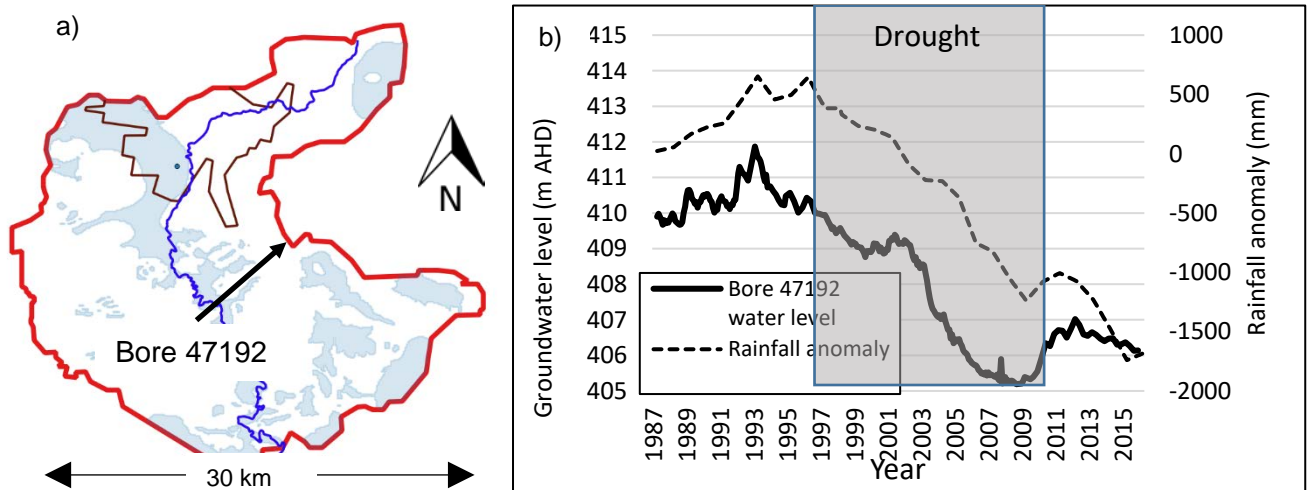


Figure 7.5: a) location of bore 47192 within the deep leads and b) Groundwater level and rainfall anomaly.

7.3.3 Quaternary Aquifer

The Quaternary sediments comprise a relatively shallow layer generally between 5 and 10 m thick, which is reflected in the median total construction bore depth of 6m. It can be seen from Figure 6a that the area of the Quaternary Aquifer is relatively small, and there is significant intersection between this and the urban area of Ballarat through which the Yarrowee River traverses (Figure 6a). While the relatively loose materials in the aquifer suggests potential water availability, the small area results in low sustainable yields. No monitored bores with available data were located within this aquifer.

The earliest settlers in Ballarat in the 1840's (Withers, 1887) describe three permanent water holes along the Yarrowee River, used for watering stock in 'the driest times'. This at a time when nearby lakes relying on surface water runoff, Burrumbeet and Learmonth, were dry. This is consistent with maps drawn for the Ballarat Water supply in 1870 (Krause, 1870) which show low-yielding, permanent springs within the Yarrowee catchment.

The initial and richest period of gold mining was in shallow alluvial soils, generally between three and five metres, and the meticulous detailing of these by Mr. Harrie Wood, District Mining Registrar (Brough Smyth, 1869) demonstrates the difficulties with water. Comments include that at "White Flat...there was a great deal of water..." (p448), in "Canadian Gully... upon the flat towards the junction of this and the Prince Regent Lead, a drift from the surface to a depth of ten or twelve feet was found, containing a large quantity of water" (p449), that in "Sailor's Gully...there is a great deal of water" (p450), the "One Eye Gully and Victoria Lead are...very wet and poor..." (p451) and "Gravel Pits Lead contains... a great deal of water..." (p455). These observations indicate the groundwater levels in the Quaternary Aquifer were

high at the time of European settlement and the early gold rush period when mining commenced in the alluvium.

There have been no monitoring bores within the Quaternary aquifer identified, consistent with it being not widely considered as a significant groundwater source, so all data is discrete information at the time of bore construction. This indicates that the watertable has dropped during the Millennium Drought (6b), with a statistically significant difference between the pre-1997 and post-1997 periods from over 440m AHD to 406m AHD. This results in the watertable dropping below the elevation of the Yarrowee River bed in the section through which it traverses this aquifer. The groundwater level within the Quaternary Aquifer, which has the porosity and transmissivity to provide some baseflow, has reduced to a level below the river bed (Figure 6b) at the same time as the groundwater baseflow has ceased (Ebbs et al. 2018), (Figure 3). As baseflow from the Basalt Aquifer has been ruled out, it is reasonable to assume that groundwater baseflow has been from the Quaternary Aquifer, and the reduction in phreatic watertable level has resulted in baseflow cessation. While there is no bore construction data following the end of the drought, the continuation of no baseflow within the Yarrowee River suggests that watertable has not recovered to previous levels.

The lack of baseflow as measured at the gauging station occurs despite the Yarrowee River continuing for some distance beyond the residential area, leaving the Quaternary Aquifer and traversing the basalt. This supports the theory that the Basalt Aquifer does not provide baseflow which had instead been from the Quaternary Aquifer.

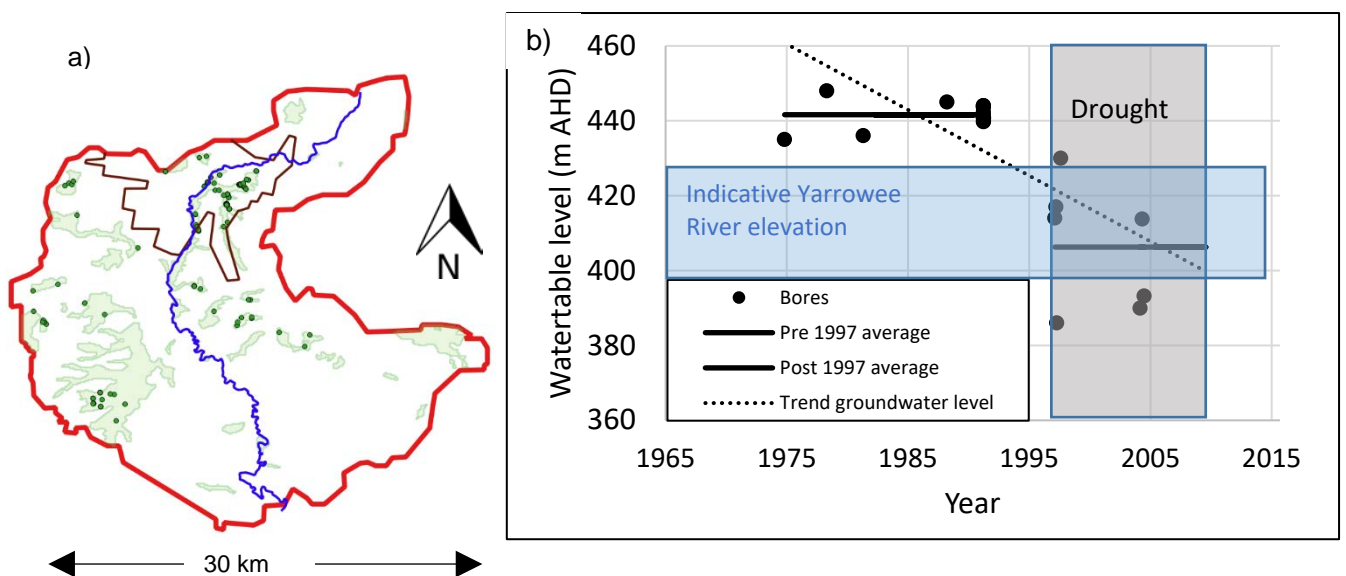


Figure 7.6: a) Quaternary aquifer and bore location and b) groundwater level with trends and averages and comparative Yarrowee River elevation.

7.3.4 Basement Aquifer

The metasediments and granites, as the basement within the Yarrowee River catchment, is represented in the aquifer maps by those areas not covered by one of the other three aquifer systems. The bores selected are those located in that portion of the aquifer connected directly to the Yarrowee River (Figure 7a).

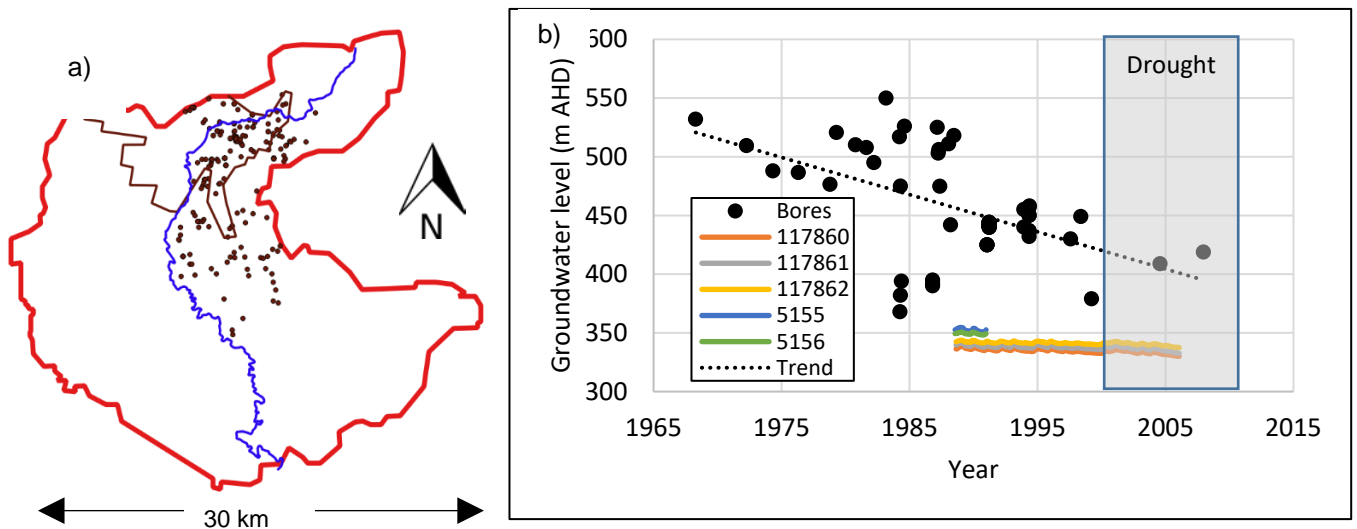


Figure 7.7: a) location of constructed bores within the Basement Aquifer adjacent to the Yarrowee River and b) groundwater level of discrete and continuously monitored observation records

The overall trend in watertable level within the Basement Aquifer is a decrease over the observed period, similarly to that in the Quaternary Aquifer. This trend is supported by those continuously monitored bores from 1989 to 2006, which show a reduction of 10m over this period which may reflect both changes in climate and mine dewatering.

The low hydraulic conductivity of the Basement Aquifer suggests that any groundwater contribution to the baseflow of the river would be small. Therefore, while the reduction in water level assists in developing an understanding of groundwater within the region, it does not alter any of the conclusions drawn about contributions to baseflow from other aquifers.

7.3.5 Catchment as importer or Exporter

The conclusion from the data regarding the basalt aquifer was that water must be being transferred to somewhere other than the Yarrowee River. To confirm this, the average river flow of the Yarrowee River for the time data is available (60 years) is compared to the average recharge rate of the catchment for the same time.

Table 7.1 – River flow and recharge rate for Yarrowee catchment

Q_R (mm/year)	76
$R = P - ET$ (mm/year)	205

Where Q_R = River flow
 R = Recharge Rate
 P = Precipitation
 ET = Evapotranspiration.

Recharge being significantly higher than stream flow indicates that the basin is a net exporter of groundwater, consistent with the observations regarding the basalt aquifer. River flow in this catchment has also been shown to be impacted by small farm dams, however this effect is 20 mm/year, one-sixth of the estimated export so does not alter the conclusion.

7.3.6 Recharge or topography controlled

An indicative WTR has been calculated for the Basalt, Quaternary and Basement aquifers within the Yarrowee River catchment (Table 2). Appreciating that data can vary considerably, and therefore the results cannot be generalised, the intention is simply to gauge a coarse resolution understanding of the aquifer systems and their interaction with the river.

Table 7.2 – Indicative Water Table Ratio for three aquifers

	Quaternary	Basalt	Basement
R (mm/year)	50	50	50
R (m/day)	0.00014	0.00014	0.00014
K (m/day)	0.1	1	0.00001
L (m)	450	5,200	6,100
d (m)	112	350	171
H (m)	7.6	53	200
R/K	0.00137	0.00014	13.7
L/d	4.0	14.9	35.7
L/H	59.2	98.1	30.5
WTR	0.33	0.20	14,904

The most significant difference between the aquifers is the hydraulic conductivity, with other parameters having relatively small impacts. The WTR clearly shows that the Quaternary and Basalt are recharge controlled aquifers while the Basement is topography controlled. Confirmation that these aquifers are recharge controlled indicates that if urbanisation has impacted recharge rates, particularly in the relatively small Quaternary Aquifer, this could result in the reduction in baseflow of the Yarrowee River.

7.3.7 Groundwater extractions

In addition to the depth of bores within each aquifer, the frequency of bore construction for exploitation of the groundwater may confirm information regarding the extent of urbanisation impact. Within the Ballarat area, all bore construction requires a Works Licence from the groundwater manager, Southern Rural Water, as defined by the Victorian Government Water

Act, 1989. If the water is to be used for irrigation or commercial use, a Groundwater Licence is also required, however this is not necessary for stock and domestic purposes.

There have been 411 registered bores constructed in the Yarrowee catchment with recorded dates of construction between 1968 and 2017 which are either for consumptive use or have not had their use recorded (Figure 8). Groundwater investigation and monitoring sites have been excluded as these do not impact the amount of water extracted. There were an additional 29 bores constructed prior to 1968 and 229 with no date of construction recorded which unfortunately cannot be included. As may be expected, the periods of highest construction rate for stock and domestic purpose were during times of restriction on reticulated urban water use within the city, which has occurred on three occasions, 1968, 1982 and 2000 – 2007. (CHW, 2016). Some data may reflect the year of registration, or data entry, rather than the actual construction year. The use of groundwater at times when surface water supplies are limited is as expected, which reinforces the potential impact as the time of least recharge due to rainfall is inherently when most demand will be placed upon the available resource.

Under the controlling legislation, areas may be declared as Groundwater Management Units (GMU) (Southern Rural Water, n.d.-a), and within these regions licenced extractions and allocations are controlled. The Yarrowee River catchment is not within a GMU, so there are no controls on the quantity extracted even as levels decline, although stock and domestic use is small compared with irrigation.

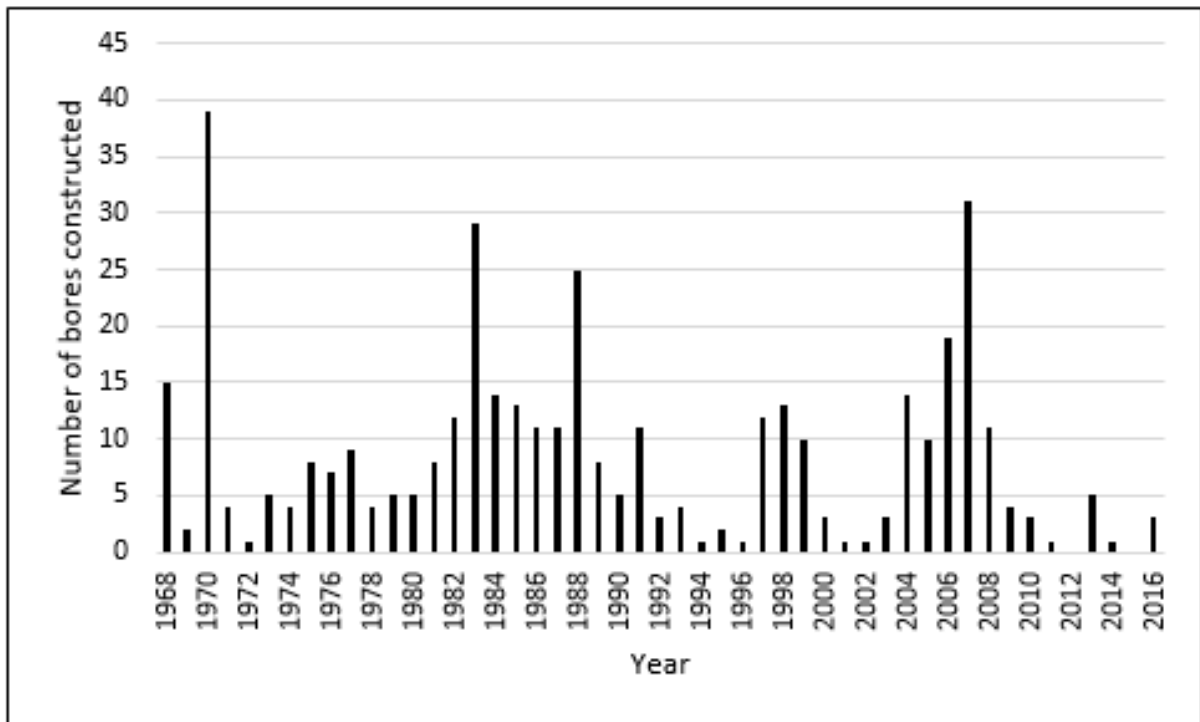


Figure 7.8: Bore construction frequency in the Yarrowee River catchment (excluding investigation and monitoring bores).

The only licensed groundwater extraction within the Yarrowee River catchment is Ballarat Goldfields mine dewatering, with no other commercial or irrigation users identified. Dewatering is from the Basement Aquifer, with a discharge license for a maximum of 300 ML of water per year into the Yarrowee River. This is less than 1% of the overall annual average river flow, but can be a significant contributor to the river baseflow during dry periods, although more than 20 times this volume, about 7,000 ML/year, is discharged from the sewage treatment plant. While the extraction of groundwater from Ballarat Goldfields has a local impact on groundwater level the Basement Aquifer transmissivity is so low these operations are unexpected to widely impact the water table.

7.4 Discussion

By combining the limited quantitative data with the more extensive evidence from qualitative accounts of historical observations and modern day empirical observations, a reasonably complete picture of the hydrogeological changes of the Ballarat region over 160 years can be derived. The evidence gathered has led to an identification of the aquifer which provides groundwater baseflow to the Yarrowee River. Identifying that this is recharge controlled with a relatively small area indicates its sensitivity to urban development.

Despite the relatively sparse monitoring bores, a situation which is typical of many regions in Australia and the world (Han *et al.*, 2017), existing data has been used to identify groundwater variation without the requirement for a specific monitoring program which is often not viable due to resource constraints and the expense of groundwater monitoring. Similar information may be available in different forms in many places of interest, making this technique widely applicable. Known causes of groundwater changes and extractions are highlighted, as is the growth of impervious surfaces. Based on the information gathered the importance of different aquifers in the provision of baseflow to the river can be determined.

While a direct relationship between urbanisation and groundwater level cannot be drawn from this data, there is a strong indication of the aquifer which has provided baseflow to the Yarrowee River. Given the relatively small aquifer area and its overlap with the urban development of Ballarat, this points to the likely cause of reduced baseflow and the starting point for further work. While acknowledging that causation cannot be assigned in historical investigations such as this, understanding the impact of urbanisation on groundwater becomes more attainable by the use of existing data.

The empirical observations of water level in the basalt aquifer, the river flow monitoring and the geology of the region support the conclusion that the basalt may not contribute significantly to the baseflow of the Yarrowee River, despite high permeability and use as a groundwater supply.

While the Basement Aquifer has shown similar changes in water depth to the Quaternary Aquifer, the low permeability of the basement means this provides much less baseflow to the Yarrowee River. Therefore changes to the groundwater level in this context are not as significant. The larger area of the aquifer compared with the Quaternary, and the watertable being controlled by topography, results in the impacts of urbanisation being less significant.

The Quaternary alluvium was known to have groundwater levels close to the surface at the time of the gold rush in Ballarat. Mining had a significant impact on the alluvium, with widespread, significant overturning of the regolith and unconsolidated alluvial sediments. This may have significantly affected the recharge rate which has been shown to control the watertable level. Having much higher transmissivity than the basement, this aquifer may be expected to provide some groundwater flow, although its relatively small size had previously resulted in it being considered less significant than the basalt. However the Yarrowee River runs through it for a significant length.

The reduction in groundwater level within the Quaternary Aquifer occurs during the same period as the reduction in baseflow of the Yarrowee River. As the groundwater levels have dropped to a similar or lower level than the elevation of the river bed, the potential for this aquifer to provide baseflow has been severely hampered. Despite its small overall area, the

circumstantial evidence and the geology of the aquifers strongly points to the Quaternary Aquifer being the most significant contributor to the Yarrowee River baseflow.

The channelisation of the Yarrowee River using stone masonry, which was completed in the 1880's throughout urban Ballarat, may have interrupted the exchange between ground and surface water, however there was significantly higher dry weather flow in the river between 1957 and 1996 than in the 1997 – 2017 (D. Ebbs *et al.*, 2018a) period suggesting there has been an additional significant impact more recently.

Being of smaller total area with a large portion of the relevant aquifer close to the residential area, the Quaternary Aquifer which provides baseflow has been subjected to a greater degree of impact from urbanisation compared with the other aquifers. The reduction in groundwater level occurs over a much shorter period of time than urbanisation expansion, indicating the reduction in recharge is related to a combination of this with the reduction in rainfall. More recent data on the depth of the watertable in the Quaternary Aquifer since the end of the Millennium Drought would provide more substantial evidence regarding the impact of urbanisation on recharge rates.

While the degree of urbanisation in a regional city may be low in comparison to major cities of the world, it is significant for the recharge of this aquifer and therefore the Yarrowee River flows. This highlights the need for understanding the groundwater and surface water interactions if the effects of urbanisation on the water cycle are to be well managed.

Groundwater baseflow is an eco-system service which an aquifer provides, and the reduction in the watertable impacts on the ability to perform this function. The recognition this work provides on the importance of an aquifer not previously considered to have major significance is an indication that greater consideration must be given to the understanding of the overall system and interactions between elements.

The case study of Ballarat has shown that existing data including historical records, artwork, geology and discrete bore records can be used in combination with the continuous bore monitoring available to provide an understanding of the impact of urbanisation on groundwater, and in this case demonstrate a new understanding of the provision of groundwater baseflow on the river.

7.5 Conclusions

Since the time of rapid settlement in Ballarat due to the gold rush, there have been profound changes to the relationship between surface water and groundwater. These include extensive mining operations overturning the regolith, sluicing which mobilised and redeposited sediments, megapores connecting aquifers, dewatering operations and

increasing coverage of the landscape with impervious surfaces. While traditional comprehensive scientific groundwater data was not readily available and no continuous groundwater monitoring exists over this time period, the legacy data that is available has been used to infer relationships between groundwater and baseflow.

By applying the principles of hydrogeological science to historical and empirical observations, a greater understanding and a likely answer to the question of the aquifer which has provided groundwater baseflow to the Yarrowee River has been reached, and links made to the urbanisation of Ballarat. Although the data is not adequate to enable detailed quantitative analysis, the long term view and the definitive results achieved without the requirement to undertake a full groundwater investigation provides a demonstration of this methodology improving the understanding of system interactions.

While the highly permeable fractured Basalt Aquifer was anticipated to provide baseflow, the data demonstrates the most significant aquifer regarding groundwater baseflow contribution has been the Quaternary alluvium. Dry weather flow in the river is now entirely due to anthropogenic sources of mine dewatering and waste water treatment plant discharge, as groundwater levels in the aquifer have reduced to levels similar or lower than the Yarrowee River bed. Urbanisation and impervious surfaces can have a major impact on the ability of the aquifer to recharge due to the relatively small surface area. This demonstrates the need to improve our understanding of the overall system, interactions between elements and the eco-system services provided if the impacts of urbanisation are to be managed.

The need for understanding the impact of urbanisation on groundwater systems is widely recognised. Historical and empirical observations will be available in many places throughout the world, and this paper provides a method for using legacy data which can enable understanding to be gained that would otherwise not be possible without extensive groundwater monitoring.

8. IMPROVING THE DECISION MAKING IN COMPLEX SITUATIONS: an Integrated Urban Water Management case study

Although the objective of this thesis has been to investigate the potential for stormwater to significantly supplement the potable water supply, it is not the only option. The decrease in the downstream river flow in Ballarat may indicate stormwater would not come without some adverse effects, however all water sources are impacted by the changes in climate, and stormwater may still be preferable to taking additional water from other river systems. Desalination of seawater and recycled wastewater could also be used. The way in which these schemes are implemented can also vary with distributed systems, third pipe networks for the supply of non-potable water, direct and indirect injection and Managed Aquifer recharge all providing opportunities in different places depending on the unique circumstances.

The common factor with the implementation of all IUWM options, as for other complex community change, is the requirement to inform the public and gain acceptance of proposed changes. As all options for implementing IUWM present different barriers, being able to demonstrate this and the reasons why particular options may be appropriate is important. One of the most widely used models for understand the ability to implement change in public utilities is the Strategic Triangle (Moore, 1995). This chapter modifies this model to create an assessment tool to compare options - called the Strategic Assessment Triangle, which is visualised using a chart named the Options Portfolio Map.

This work has been submitted for peer review to the Australasian Journal of Water Resources where the paper is in the process of being revised. This revised version has been presented here and was due to be re-submitted at the time of writing.

8.1 Abstract

Integrated Urban Water Management (IUWM) offers multiple benefits, although implementing change such as this involves multiple organisations and stakeholders. One widely used model to describe the factors determining the ability to create change in the public sector is the Strategic Triangle, which shows that for change to be successful value, legitimacy and capability must be demonstrated.

Many techniques are available for determining the preferred option from a range of possibilities, with economic decisions being the most widely used. When externalities are included they may be given a value or weighting to enable the best answer to be determined. This paper looks at alternative assessment options and then describes a technique termed the Strategic Assessment Triangle, which provides an assessment on the scales known to be of importance in implementing change and displaying these via the Opportunity Portfolio Map. This enables the complexity of the decision to be maintained, provides flexibility to allow for uncertainty and can induce a broader discussion as to why alternatives may be favoured under specific conditions. A case study of all the potential solutions for IUWM in Ballarat is then used to illustrate the technique.

The Strategic Assessment Triangle and the Opportunity Portfolio Map provide another method for assessing and displaying comparative assessment information, and this enhances the discussion regarding implementation in complex environments. Competing factors often leads to contested decision making, and a technique which enables multiple criteria to be presented and adjusted can improve the analysis

8.2 Introduction

IUWM offers multiple benefits that span improved amenity in the lived environment, better environmental outcomes for receiving waterways and additional water resources that can supplement, or even replace, current supplies. While it has been recognised and discussed for over 60 years (Angelakis & Xiao, 2015; Argue & Barton, 2007; Biswas, 2004), increasing urbanisation and demand on existing potable water supplies (McDonald *et al.*, 2014) have refocussed attention. The concept of a water sensitive city (Brown *et al.*, 2008) has created a vision of increased urban amenity, reuse of water, reduced heat island effects, lower demands on existing water supplies and a reduction of waste streams. The focus in this thesis has been on the use of stormwater as an alternative water supply, but it is not the only option and choices are required. As with many complex issues such as the urban water cycle, implementation is difficult (Brown, 2005; Camilleri & Trowsdale, 2012; Roy *et al.*, 2008), and the multiple factors involved represent a complex decision making process, however this is not unique.

Significant change within government and society often involves multiple organisations and stakeholders, the requirement for assessing alternative solutions to problems with multiple factors is common, with 'most problems of the modern era being described as wicked' (McGrail, 2014). To achieve change, which inherently involves risk and overcoming inertia, the reason must be demonstrated, or as described in Kotter's seminal work on change management (Kotter, 1995), a sense of urgency created. However, while demonstrating the need is a prerequisite, it alone does not determine the probability of successful implementation. Barriers to IUWM that have been identified include the institutional arrangements of water management (de Haan *et al.*, 2014; Ferguson *et al.*, 2012; Livingston, 2008; Moglia *et al.*, 2011), public acceptance (Hurlimann & Dolnicar, 2010), and the inability of the current economic models to consider externalities and the total benefits. The socio-political nature of the problem has been discussed in work on the multi-level governance requirements to achieve progress (Daniell *et al.*, 2014; Patouillard & Forest, 2011), while the changing boundaries of what must be included in an integrated or systems approach can be considered a semantic exercise (Biswas, 2004), a standard boundary definition problem (Mitchell, 2004) or a revolutionary approach (Coombes *et al.*, 2016).

While decision making with one dimension (Return on Investment for example) is relatively simple, when multiple dimensions are included (the trade-off between cost, quality and time for example) then this process become inherently more difficult. Assessing problems with multi-dimensions is commonly required, however methods for undertaking and conveying assessment of these have shortcomings. Economic assessments have been the pre-

dominant criteria for determining optimum solutions since the ascension of neo-liberal economics in the 1970's. Within economics there is an understanding that externalities must be considered, however as by definition the cost of these is not borne by those responsible, the inclusion and assignation of these costs has proved problematic. As more factors are included for consideration including social, legal, political, environmental and ethical impacts, then the analysis becomes more complex. However, it is necessary that this occurs. During the final decision making process after detailed assessments have been undertaken there may be adequate information and resources to undertake analysis of multiple criteria, however options must be considered throughout all stages of an assessment process. It is also necessary that the assessment criteria is communicated readily, and barriers, weaknesses or concerns readily identified so that the logic and integrity of the decision making process is maintained.

A range of methods exist for comparative and strategic analysis. Commonly used decision assessment tools are described, and the strengths and weaknesses are discussed. A method is then described for using the most rigorous of these analyses, using a well-known change management framework to combine these results in a format that can easily convey the different challenges faced by alternative decisions. A case study of all the potential solutions for IUWM in Ballarat is then used to illustrate the technique.

8.3 Assessment Tools

8.3.1 Economic Assessment

Economic assessments for complex problems rely on all factors being attributed a monetary value. This may be described as the consumer's willingness to pay, or the eco-system service provided for example. The value of bio-diversity can be calculated because a percentage of the population is willing to pay some greater amount to use a river that is in vibrant health compared to one that is not. Alternatively, the value of tourism and other commercial enterprises is known and relies upon the river health, providing a calculable value. The complexity of these approaches and difficulty in calculating an agreed value can be easily recognised, even in this relatively simplistic example. Proponents of economic assessment claim that it best reflects how society operates, valuing externalities is possible and if there is no recognisable willingness to pay, then there is no real value.

While many environmental economists have embraced this approach, an alternative view is that once a monetary value is placed on 'intangibles' then the argument is being conducted in the economic domain rather than taking a societal view where other considerations must be accentuated. Three perspectives can be considered, each with a different outlook on the

value of economics when understanding eco-system services (Farley, 2012). If the service is essential, then comparative economic analysis is inappropriate. Access and entitlement to eco-system services frames justice considerations, and conflicts caused by alternative uses demonstrate this, although this is an issue of social construct rather than economics. Economic analysis is predicated around the third perspective of efficient allocation of scarce resources.

Economic analysis is important, and must be included in robust comparative analyses. It may be possible to include all factors and externalities in an economic assessment to obtain an accurate reflection on the best options, however the complexity required to do this results in it rarely occurring. If the true cost of other factors, social, technological, environmental, political, legal and ethical issues for example, are not effectively considered in the economic assessment, then there must be an alternative method for considering these in the comparative analysis.

8.3.2 Multi-Criteria Decision Matrices

Multi Criteria Decision Matrices (MCDM's) use numerical techniques to optimise a range of weighted variables to produce the best solution from those available (Triantaphyllou, 2000). They rely on the criteria used for assessment being agreed and the impact of each variable on the outcome being understood. There have been many variations of MCDM's developed to improve the optimisation and overcome the requirement for precise data (Velasquez & Hester, 2013). These include alternative weighting techniques and the use of fuzzy logic. While they are widely used the fundamental design assumes a single assessment criteria which can be optimised, and this is also the essence of their limitation. While excellent for ensuring economics are optimised, with the elasticity of all variables to cost being calculable, the ability to include the relative importance of ethics, the justice of alternative access and the sustainability of the environment is questionable. While the relative merits of these issues will always be the basis of discussion in any decision making process, the production of a single, optimum result which supposedly embraces this complexity may be considered to only manage this superficially.

MCDM's are widely used and optimisation techniques can ensure the best result from the alternatives presented if the effect on the result criteria are known, however the process of producing a single criteria can have the impact of simplification. While the results can appear definitive they are achieved by determining relative effects and therefore the discussion about the merits and assumptions behind these can simply replace those which had been occurring about alternative solutions producing no overall improvement in understanding.

8.3.3 Triple Bottom Line or Sustainability Analysis

The Triple Bottom Line (TBL) is a term coined by John Elkington and popularised in the book 'Cannibals with Forks: the Triple Bottom Line of 21st Century Business' (Elkington, 1997). It describes how businesses not only have to manage and report the 'bottom line', they must also manage and report environmental and social impacts. However, the term TBL which was envisioned to capture the broad spectrum of requirements which must be managed now more commonly describes a multi-criteria decision making process considering economic, social and environmental factors. Business reporting of social and environmental performance is now often called Sustainability Reporting, and to this end the Global Reporting Initiative has developed global reporting standards (Global Reporting Initiative, 2016). Reviews of TBL and Sustainability Reporting highlight that environmental and social reporting is, however, selective, less rigorous than financial reporting, and almost always subservient to it (Gray & Milne, 2002; Pennington & More, 2010).

Guidelines for the use of TBL in stormwater re-use projects have been published (Taylor, 2005). This is a rigorous technique where a range of criteria are generated for each category and given an overall rating. After analysis, the best overall solution is determined (Taylor & Fletcher, 2006). This is a particular case of an MCDM where the broad categories if not the criteria within them have been fixed. As such, it has the same inherent weaknesses regarding the relative effect score and the simplification of a single answer. The move away from TBL accounting to sustainability reporting which has a less prescriptive methodology is indicative of the associated problems.

8.3.4 SWOT Analysis

An analysis of Strengths, Weaknesses, Opportunities and Threats (SWOT) is most often done as a strategic planning initiative for organisations or individuals. It can however be used as an initial sorting tool for comparative analysis.

Unlike MCDM techniques it is qualitative, gathering information regarding alternatives rather than scoring on what may be described as contrived scales, particularly at the early stages of assessment. Potential economic returns (Opportunities), barriers to implementation of an idea (Weaknesses or Threats), drivers (Strengths) and alternative solutions (Threats) can all be highlighted. As a purely qualitative tool it provides valuable information but may be less useful in drawing conclusions.

8.3.5 Risk Management

An alternative to economic analysis or MCDM's which are designed to determine which option is best is to understand what approach entails the lowest risk. Widely used in safety, it can be applied to all areas as described in ISO31000:2009. The standard provides a framework for analysing risk, describing how the situation must first be understood, a process for identifying, analysing and evaluating the risks undertaken, applying a solution and then reviewing and repeating the cycle, a summary of which is provided in Figure 1. While this is widely applicable, and similar to other frameworks such as PDCA (Plan, Do, Check, Adjust) it is not a prescriptive methodology for determining a favoured option, or identifying barriers to implementation.

Risk management best describes what drives the approach of the water industry in Victoria. The Essential Services Commission (ESC) regulates the sector by approving and assessing prices and monitoring performance against developed codes and guidelines. The water utilities must then meet these requirements, with penalties for not doing so.

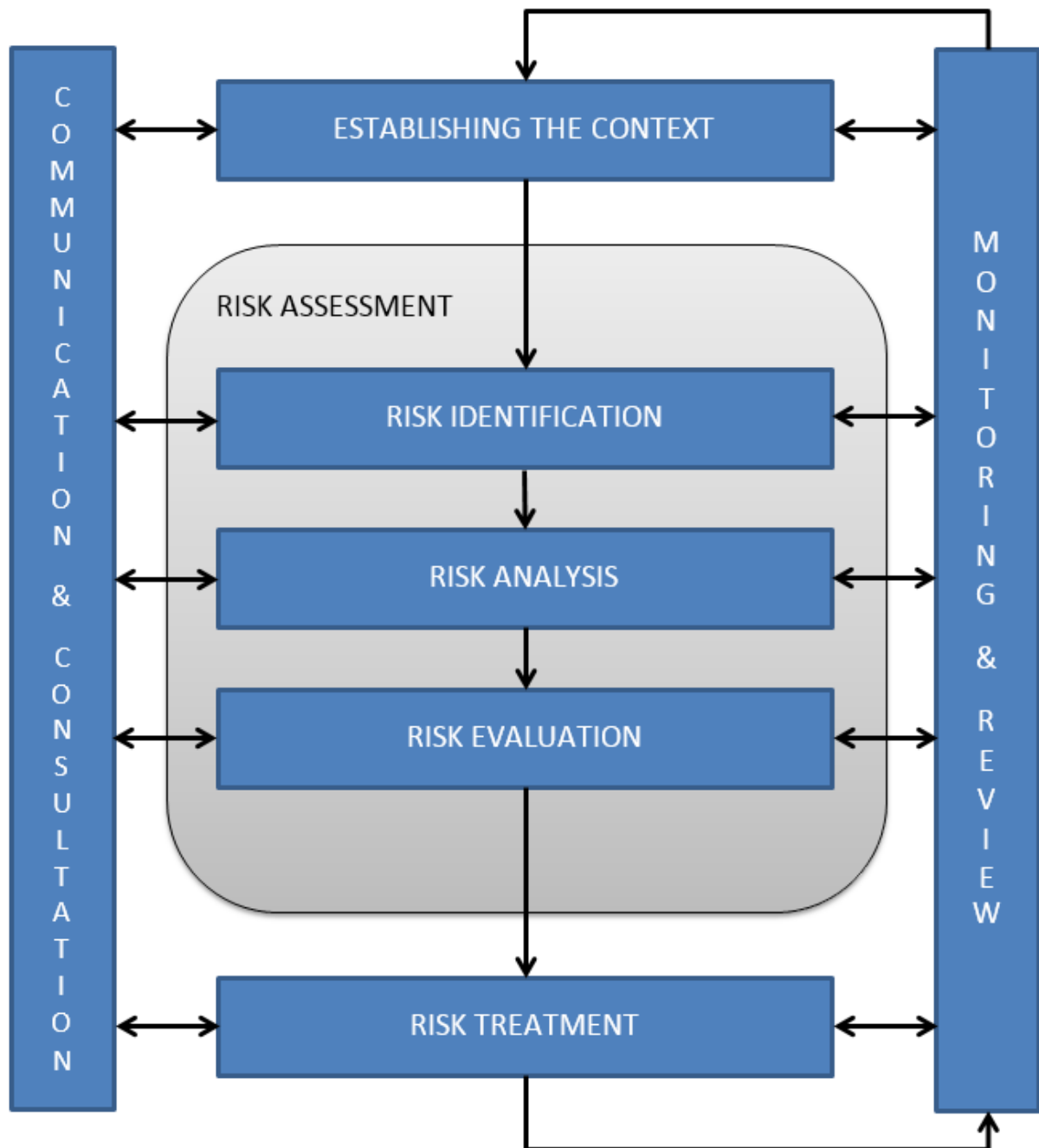


Figure 8.1 - Risk Management Process (from ISO31000:2009)

8.3.6 STEEPLE Analysis

A common method for undertaking comparisons in the business community is a STEEPLE analysis (Walden, 2011), which considers social, technological, economic, environmental, political, legal and ethical issues. Analysis of these forces on decision making is broadly acknowledged and there is no known developer of this technique (Lenz & Engledow, 1986) which has evolved through various phases over the past fifty years, having been known as PEST, STEEP and PESTLE.

This is also a qualitative tool which may be favoured due to its specific categories ensuring all aspects influencing decision making are considered.

8.4 A modified technique

When assessing the options available for the comparative analysis of complex problems there would be advantages in having a tool that

- a. Considered all the known influences on the decision making process
- b. Scored those categories to enable comparison
- c. Allowed for uncertainty
- d. Was based on widely understood methods
- e. Enabled visual comparisons

One widely used model describing the ability to implement change in the public sector, and more recently the private sector also, is the Strategic Triangle (Moore, 1995). It requires answers to three questions for change management to be successful: 1) what's the value being created, 2) where's the legitimacy and support going to come from, and 3) what kind of operational capacity is needed? While 'value' can have different meanings, it may be agreed that for a change to be successfully implemented there must be some sense that it will lead to an improvement. However, Moore shows that being better is not adequate, those making the decision must have legitimacy, or social licence to make the change, and the capability to implement the proposal.

8.4.1 The Strategic Assessment Triangle

The Strategic Assessment Triangle maps the seven categories of the STEEPLE analysis to the three axes of the Strategic Triangle which have been shown to indicate the likelihood of change being successfully implemented. It uses a Multi Criteria Decision Matrix to score these categories to enable. While this process may not produce any new information, it is transforming something that has been produced with rigorous analysis but can be daunting and difficult to convey into a form that is readily understood.

Table 8.1– Transforming STEEPLE Analysis to the Strategic Assessment Triangle

Strategic Triangle Category	STEEPLE Category	Comment for IUWM
Value	Economic	While value can be considered more widely than economics, an economic assessment will be included in most decision making. The breadth of this economic analysis can be determined and could include externalities such as the environment, but given the contestability of that process and the ability of other areas to remain within the analysis, they have not been in this example
Capability	Socio-political Technological	The importance of the socio-political interface and multi-level governance on the ability to implement IUWM has been discussed, but there must be an ability to work across existing boundaries if IUWM is to be successful. Technical capability must also be compared and is important when R&D activities are being compared with widely used technology which may not be such an issue for IUWM.
Social Licence	Social Political Environmental Legal Ethical	Community Acceptance has been identified as a key factor in the success or failure of implementing alternative water supplies. Current regulation may favour some alternatives. The environmental impact will affect the legitimacy of decisions, as will the legal and ethical implications.

The transformation of qualitative STEEPLE analysis to a quantitative result suitable for plotting on a matrix is inherently problematic, as discussed earlier in the description of MCDM's. Relative weightings and scores will always provide cause for discussion. However, reducing the emphasis on the numeric result by using a visual tool for comparative analysis, and framing the discussion around the consideration of value, capability and social licence can result in a more emphasis on assessing and overcoming the barriers to the implementation of different options. The method for completing this can be as

comprehensive and detailed as appropriate. At early assessment stages this may be relatively simple, and as more information becomes available greater detail can be added

8.4.2 The Opportunity Portfolio Map

The Opportunity Portfolio Map is based on the idea of the 'Option Space' (Luehrman, 1998), in that rather than a specific result being the determinant, the general position on the matrix is considered with an understanding there is uncertainty and information will vary over time. The Option Space is an economic tool developed for guiding investment, where uncertainty and volatility of information, and how these vary with time and circumstances, produced a six category matrix for when and how likely investment should be.

1. Now
2. Probably later
3. Maybe later
4. Maybe never
5. Probably never
6. Never

The idea that uncertainty can be accepted, information and the importance of it will change over time and the relativity of the information is important, need to be considered when making complex decisions. Reframing the conversation from 'Desalination is the best answer as it has the lowest risk' to 'Currently, desalination has the lowest risk despite the potential higher cost as the technical and organisational capability exists, and there is no social licence for recycled water', provides an understanding of why decisions have been made and what would need to change for a different decision to be made.

The Opportunity Portfolio Map does this by simply displaying the numeric results of the Strategic Assessment Triangle on to a two-dimensional matrix of Social Licence and Capability, with the Value dimension demonstrated by the size of the attribute, as in a bubble plot. The four quadrants of the map are therefore:

1. Low licence, low capability (Probably not to be implemented)
2. Low licence, capable (Could be implemented but community engagement is required)
3. Licenced, but low capability (Desired, but the wherewithal to deliver does not exist)
4. Licenced and Capable (Ready to implement)

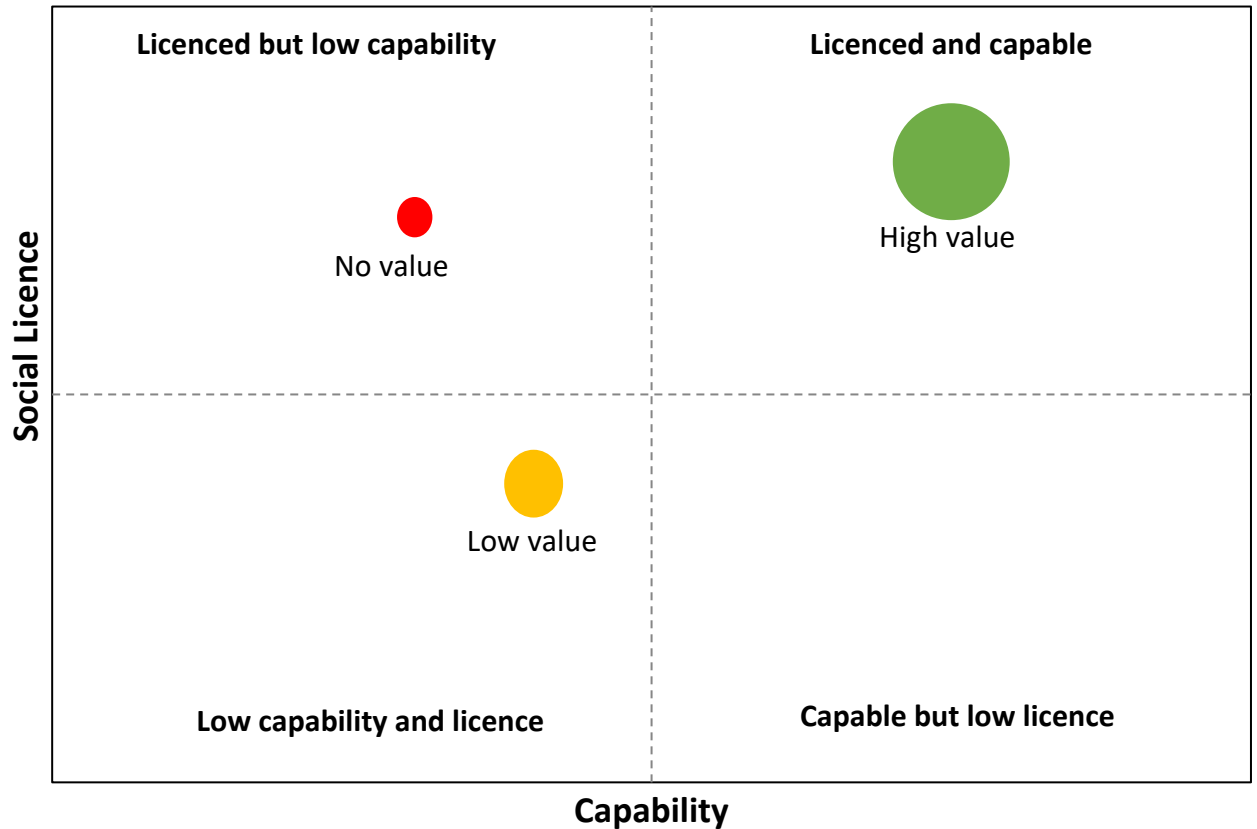


Figure 8.2 – Example Opportunity Portfolio Map

8.5 Results

8.5.1 Case Study

During the Millennium Drought (1997 – 2010), Ballarat faced the real prospect of running out of potable water and alternative water supplies were required. This resulted in the installation of the 'Goldfields Superpipe' which transfers water from the Northern Victorian Waranga Basin to Ballarat, a decision which can be understood given the short time frame and low risk of this approach (AECOM, 2010). However, other options are available to supplement Ballarat's water supply. These will be considered using the Strategic Assessment Framework and Opportunity Portfolio Map to determine what insights can be provided.

Identified options for alternative water supply are listed with a short description in Table 2. A STEEPLE analysis has been done for each of these, based on a literature review and available information gained during previous publications within this thesis. A Rubric based on the key information for Ballarat was developed to enable scoring for each of the dimensions in the Strategic Assessment Triangle. This is not a definitive process. It will be different based on the unique circumstances for each assessment, and weightings may be dependent upon the values of those undertaking the work. The objective is to determine whether a different perspective in assessing results can assist in understanding, particularly among the wider community who provide the social licence, and between authorities who must work together differently if IUWM is to be implemented successfully.

Table 8.2 – Alternative water supply options for Ballarat

	Alternative Water Supply	Description
1	Stormwater collected locally for non-potable use	The largest stormwater use scheme in Ballarat has water treated and stored in wetlands and diverted to Lake Wendouree. In addition to cleaning the water, the wetlands provide amenity for the community and habitat for wildlife. Sporting grounds also capture water, predominantly in tanks although golf clubs have dams, which are then used for irrigation. The focus on the use of stormwater for these purposes was the focus of the stormwater plan for Ballarat (Rossiter, 2013). However, as discussed in Chapter 4, this is less than 5% of Ballarat’s total water use.
2	Stormwater with Managed Aquifer Recharge for non-potable use	Industrial use is an opportunity for non-potable water and is approximately 30% of the total city water use, and 80% of domestic use is non-potable. The use of Managed Aquifer recharge for storage reduces the issue of matching supply with availability which hinders the introduction of industrial and domestic ‘third pipe’ schemes. The low domestic use of water outside the home, as described in Chapter 5, reduces the incentive.
3	Stormwater for potable use – above ground storage	<p>The use of stormwater for potable supply overcomes the difficulty of matching demand with whatever supply is available, and eliminates the need to implement additional distribution infrastructure. Peak supply will exceed demand so storage will be required. As land is expensive within the city boundary, it realistically must be located downstream of the city. Pumping will then be required back into the potable water distribution system. While stormwater is relatively clean, there is the possibility of spot contamination. Monitoring of the storage and water treatment will be required, as for the supply from the existing controlled catchments but with higher contaminant levels. Water treatment producing similar quality to that currently in place for potable supplies will be required, but for a product with higher potential contaminant levels.</p> <p>As the water is not from a controlled catchment there would be lower implications of public access to the storage, so recreation may be possible on the new lake, providing increased amenity for the town. It could be possible to build this as an off-stream storage where excess flow is diverted, enabling a flow regime in the river to more closely resemble that of pre-development conditions.</p>

4	Stormwater with Managed Aquifer Recharge for potable supply	Building storage dams is problematic due to land availability close to the city and the disruption they have caused to the flow of many rivers. Managed Aquifer Recharge (MAR) eliminates the need for a surface reservoir. This has been implemented in over 50 locations in Adelaide for stormwater reclamation, and is also done in Perth, California and other locations where groundwater is regularly used for potable supply. MAR has been trialled in the west of Ballarat, using runoff from new industrial buildings. As this rainwater was free of contaminants no treatment was required prior to charging into the aquifer, however the scheme was estimated as having a higher cost than inter-basin transfers.
5	Rainwater tanks	Rainwater tanks were encouraged during the Millennium Drought to supply garden water and toilet flushing. They are widely installed in new homes for these purposes. The use of water external to the home has been shown to be less than 20% (Chapter 5) and higher utilisation of rainwater tanks will require greater use within the house, hot water systems being suggested in literature. Reports for Ballarat indicates between 20 and 40% of the potable water supply could be substituted (AECOM, 2011).
	Recycled wastewater for non-potable purposes	Wastewater from Ballarat North Sewage Treatment Plant can be further processed through a further three stages, chlorination, UV disinfection and ultrafiltration to provide Class A recycled water. This is currently used for supply to Lake Wendouree and irrigation of school sporting facilities. It could also be used for industrial purposes. While sewage flow is higher during rainfall events, supply is more consistent than stormwater minimising the need for storage.
6	Recycled wastewater for indirect potable use	Class A recycled water meets the standards of potable water but has higher risk due to its source. Injection into an aquifer for longer term storage and potential additional environmental cleaning could minimise this concern. It also removes the need for matching with particular demand, and providing delivery infrastructure to each end user.
7	Recycled wastewater for direct potable use	Rather than the expense and difficulty of charging the recycled wastewater into an aquifer, it could be added directly to the storage reservoir. This contains water for 2 years supply in Ballarat when full, so provides adequate dilution and time for reaction if problems did occur.
8	Desalination	Ballarat's main water storage, Lal Lal Reservoir is a shared resource with Geelong, a larger coastal city. A desalination plant at Geelong could be used to provide water to Lal Lal Reservoir, and then supply Ballarat. Alternatively, given a Victoria wide water grid, excess capacity of the Melbourne desalination plant can provide water to Ballarat, either directly or by substitution of transfers

9	Inter-basin transfers	Inter-basin transfers from the irrigation areas in northern Victoria provide water that is currently traded to a high value user with the capacity to pay. The total quantity of water used by the Ballarat is less than 1% of the annual flows through the Waranga basin.
10	Superpipe	The base case for comparison – the decision that was taken to pipe water from the Waranga basin to Ballarat

8.5.2 STEEPLE Analysis for alternative water supply options

In the following pages each table assesses one of the ten options for water supply using the STEEPLE analysis

Table 8.3 - Stormwater collected locally for non-potable use

Social	<p>Use of stormwater for public space irrigation including sporting fields has widespread support</p> <p>Stormwater and public open space is often both council responsibility, so is achieved within one authority</p> <p>A Ballarat stormwater management plan implemented a number of schemes, the largest of which is supplying Lake Wendouree with stormwater, via wetlands</p>
Technical	<p>Total stormwater use identified is less than 5% of the potable water supply</p> <p>Total water flow has been impacted by factors other than impervious surfaces, so flow in addition to pre-development flow cannot be assumed</p>
Economic	<p>Collection and use of stormwater for watering Public Open Space has been identified as a low cost option</p>
Environment	<p>Storage will reduce peak flows</p> <p>Reducing directly connected imperviousness can assist in creating a flow regime closer to pre-development</p>
Political	<p>Aligns with the policy statement of Victorian Government on alternative water supplies</p> <p>No regulatory change is required to enable stormwater use</p>
Legal	<p>No legal issues have been identified with the use of stormwater</p>
Ethical	<p>Water rights, communities using water that is not then available downstream and impact of development on downstream communities can create ethical issues. Use of stormwater will prevent an equivalent inter-basin transfer occurring, so the cost of one community is the benefit of another.</p>

Table 8.4 - Stormwater with Managed Aquifer Recharge for non-potable use

Social	Use of stormwater for public space irrigation including sporting fields has widespread support 'Third pipe' schemes in new developments have been proposed, but proved difficult to implement with many authorities involved
Technical	Total stormwater use identified is less than 5% of the potable water supply Total water flow has been impacted by factors other than impervious surfaces, so flow in addition to pre-development flow cannot be assumed
Economic	Third pipe schemes rely on duplication of infrastructure in new suburbs, and retrofitting distribution into existing suburbs
Environment	Storage will reduce peak flows Reducing directly connected imperviousness can assist in creating a flow regime closer to pre-development
Political	Aligns with the policy statement of Victorian Government on alternative water supplies No regulatory change is required to enable stormwater use
Legal	No legal issues have been identified with the use of stormwater
Ethical	Water rights, communities using water that is not then available downstream and impact of development on downstream communities can create ethical issues. Use of stormwater will prevent an equivalent inter-basin transfer occurring, so the cost of one community is the benefit of another.

Table 8.5 - Stormwater for potable use – above ground storage

Social	<p>Use of stormwater for potable use is not currently widely accepted by the community, but is considered more highly than wastewater recycling. As stormwater and wastewater discharge into the same river in Ballarat, upstream of suitable above ground storage locations, separation would create additional costs.</p> <p>Social amenity could be improved by the provision of a recreational lake.</p> <p>The control of the water becomes a multi-authority issue, as storage, treatment and supply is currently managed by a different authority (CHW) to stormwater (City of Ballarat) and the Yarrowee River (Corangamite CMA and Southern Rural Water)</p>
Technical	<p>Establishing pre-development flows within the river relies on diverting peak flows, but only when appropriate. While this is not theoretically difficult, it is not widely practised.</p> <p>Total water flow has been impacted by factors other than impervious surfaces, so flow in addition to pre-development flow cannot be assumed</p>
Economic	<p>Additional treatment and controls to ensure quality as good as the current water supply will be required, and inherently more expensive than that from a protected catchment. As the storage must be downstream of the city, there will be pumping costs associated. Additional treatment costs will be offset when compared with a non-potable scheme by not having a requirement for separate distribution.</p>
Environment	<p>Centralised downstream storage does not provide any environmental benefit to the smaller tributaries throughout the city area which can be impacted by development – the effect can only be downstream of the storage.</p>
Political	<p>Aligns with the policy statement of Victorian Government on alternative water supplies, although the construction of major storage may conflict with the ‘no new dams’ pronouncement</p> <p>No regulatory change is required to enable stormwater use</p>
Legal	<p>No legal issues have been identified with the use of stormwater</p>
Ethical	<p>Water rights, communities using water that is not then available downstream and impact of development on downstream communities can create ethical issues. Use of stormwater will prevent an equivalent inter-basin transfer occurring, so the cost of one community is the benefit of another.</p>

Table 8.6 - Stormwater for potable use - Managed Aquifer Recharge

Social	<p>Groundwater has previously been used to supplement Ballarat’s water supply</p> <p>Multiple authority co-operation for local schemes of this nature have proved difficult, with EPA, Southern Rural Water, Corangamite Catchment Authority, City of Ballarat and Central Highlands Water all have some regulatory input into the process</p>
Technical	<p>Water quality must be ensured prior to charging the aquifer</p> <p>Losses from the aquifer due to transmissive flows are not known</p> <p>Water from the aquifer must be treated prior to input to the potable supply</p> <p>Total water flow has been impacted by factors other than impervious surfaces, so flow in addition to pre-development flow cannot be assumed</p> <p>Diversion from one part of the city to the aquifer will have a lesser impact on the overall water supply</p>
Economic	<p>Trials indicated higher direct water costs from this proposal compared with inter-basin transfers</p> <p>Natural storage results in a lower expected cost than an equivalent above ground scheme, consistent with the experience from Adelaide</p>
Environment	<p>Changes to the aquifer may be experienced over a longer time frame than water monitoring generally considers</p> <p>Any water diverted to the aquifer is not available to the river which has lower flows due to other changes in the catchment</p>
Political	<p>Aligns with the policy statement of Victorian Government on alternative water supplies</p> <p>No regulatory change is required to enable stormwater use</p>
Legal	<p>No legal issues have been identified with the use of stormwater</p>
Ethical	<p>Water rights, communities using water that is not then available downstream and impact of development on downstream communities can create ethical issues. Use of stormwater will prevent an equivalent inter-basin transfer occurring, so the cost of one community is the benefit of another.</p>

Table 8.7 - Rainwater tanks

Social	Community has control over some part of the water supply
Technical	Maintenance of systems and cross contamination have been identified as issues Potable water substituted may not exceed 20% of the total supply
Economic	Water supply estimated at \$3/kL, which is similar to the total cost of water in Ballarat Capital cost is borne by the consumer, but they do not receive credit for the avoided cost of the authority Major benefits may have been achieved with low external water use and newer houses having water tanks for toilet supply.
Environment	Reduces peak flows from roofs, improving the flow regime of local streams
Political	Aligns with the policy statement of Victorian Government on alternative water supplies No regulatory change is required to enable the use of rainwater tanks
Legal	No legal issues have been identified with the use of rainwater tanks
Ethical	Water rights, communities using water that is not then available downstream and impact of development on downstream communities can create ethical issues. Use of stormwater will prevent an equivalent inter-basin transfer occurring, so the cost of one community is the benefit of another.

Table 8.8 - Recycled wastewater for non-potable purposes

Social	Ballarat has implemented a wastewater recycling scheme for filling Lake Wendouree and watering school and sporting ovals
Technical	Technology to clean water to the appropriate standard is well understood Total wastewater is 80% of the water supply, as is non-potable use, so the potential benefit is high Separate distribution is required
Economic	Class A recycled wastewater is not cheaper than the potable water supply, so this is currently undertaken for projects that would otherwise have an insecure supply or perceived social benefits.
Environment	Discharge from the treatment process has a higher contaminant concentration Wastewater is currently a necessary flow for the rivers, and would not be replaced by inter-basin transfers
Political	Aligns with the policy statement of Victorian Government on alternative water supplies No regulatory change is required to enable the use of Class A recycled water for irrigation purposes
Legal	No legal issues have been identified with the use of Class A recycled water for irrigation purposes
Ethical	The use of waste streams within the community does increase the risk profile, and can be considered an ethical concern

Table 8.9 - Recycled wastewater for indirect potable use

Social	Reluctance of the community to drink recycled wastewater, although the buffer may provide adequate confidence
Technical	While the technology is in place to produce acceptable water from wastewater, future contaminants are unknown and recycling will result in a build-up of impurities if these are not removed Storage is required for the buffer between production and use, rather than intermittent supply
Economic	Literature review indicates this is higher cost than using stormwater due to the higher treatment costs, with storage required in both cases
Environment	Injecting recycled wastewater into an aquifer will require long term monitoring to manage the impact Waste stream from the treatment process has a higher contaminant concentration Wastewater is currently a necessary flow for the rivers, and would not be replaced by inter-basin transfers May lead to people drinking bottled water to avoid recycled wastewater
Political	Non-preferred within the Australian Drinking Water Guidelines due to the higher risk Lower risk options are preferred within the current policy framework
Legal	The water supply authority has responsibility for the quality of the water supply, and while this would remain the risk and sensitivity may increase
Ethical	Replacing a water supply that does not currently use wastewater with one that does without any alternative may be seen as unethical

Table 8.10 - Recycled wastewater for direct potable use

Social	Reluctance of the community to drink recycled wastewater, particularly without an environmental buffer
Technical	While the technology is in place to produce acceptable water from wastewater, future contaminants are unknown and recycling will result in a build-up of impurities if these are not removed
Economic	Treatment costs are higher than for stormwater, but as no additional storage is required, the overall economics are favourable
Environment	Waste stream from the treatment process has a higher contaminant concentration Wastewater is currently a necessary flow for the rivers, and would not be replaced by inter-basin transfers May lead to people drinking bottled water to avoid recycled wastewater
Political	Non-preferred within the Australian Drinking Water Guidelines due to the higher risk Lower risk options are preferred within the current policy framework
Legal	The water supply authority has responsibility for the quality of the water supply, and while this would remain the risk and sensitivity may increase
Ethical	Replacing a water supply that does not currently use wastewater with one that does without any alternative may be seen as unethical

Table 8.11 - Desalination

Social	Concern with the high energy use and high capital and maintenance cost for a facility with intermittent use
Technical	Well understood process that is used in many parts of the world
Economic	Sea water has much higher levels of contaminants than stormwater or sewage, resulting in higher operating costs Water must be pumped 100km
Environment	High energy use High concentration discharge Environmental flows in the Moorabool River are managed with transfers of water from Lal Lal Reservoir to Geelong, which may change
Political	Identified as a rainfall independent, low risk source of potable water
Legal	No legal issues have been identified with the use of desalinated sea water
Ethical	Use of desalinated sea water will prevent an equivalent inter-basin transfer occurring

Table 8.12 - Superpipe

Social	Concern regarding fairness and transfer of productive water (irrigation) to consumptive use within a city
Technical	No additional resource is created Water supply is limited only by infrastructure sizing
Economic	Water trading should result in resource being used most productively as represented by the highest price being paid, however urban users have a much higher capacity to pay than irrigators
Environment	Water transferred into the Ballarat area will benefit the local rivers at the cost to the basins in northern Victoria
Political	Water trading is current policy within the Victorian Government to ensure the highest value is generated from the available resource
Legal	No legal issues have been identified with inter-basin transfers
Ethical	Inter-basin transfers can create ethical issues regarding water rights

8.5.3 Mapping STEEPLE results to the Strategic Assessment Triangle

8.5.3.1 Social Licence assessment of alternative water use options

When mapping the STEEPLE analysis to the Social Licence value, significant impacts for Ballarat must be considered. No significant legal or ethical issues were identified for any of the alternative water supply options so as these will not differentiate between options they have not been included in this process. Five major factors were identified impacting the social licence to implement change to the water supply within Ballarat; community support, political and regulatory requirements, public health impacts, the effect on other elements of IUWM and environmental impact. A rubric developed to rate each of these with a score from 0 – 5, and the sum of these scores provides the overall Social Licence value.

8.5.3.2 Capability assessment of alternative water use options

Three factors regarding the capability to implement IUWM initiatives have been identified, and similarly to the social licence assessment a rubric has been developed. The factors included are the potential impact on potable water supply, the technical status of the proposal, and whether significant organisational change is required within the water authorities.

Table 8.13 - Social Licence Impact for IUWM implementation in Ballarat

Criteria	0	1	2	3	4	5
Community Support	Community is unlikely to support this change	A significant crisis or long term education campaigns will be required to gain community support	While there may be some support, the community is generally against this proposal	The community has mixed feelings	There is some community support for this proposal but the majority are indifferent	The community supports this proposal
Political	Changes to government policy and regulation to enable this project are unlikely	Significant policy and regulatory change is required	Policy and regulatory is required but may be expected to occur in the future	Policy and regulatory is required but may be anticipated within the foreseeable future	Policy and regulatory changes to enable this project are not expected to hinder progress	Within current policy and regulatory framework
Public Health	Water source is likely to increase public health concerns	Significant additional controls are required to maintain public health	Some additional controls are required to maintain public health	Public health is not considered to decrease, but risk has been identified.	Increase in public health risk is not significantly worse than a controlled catchment	Water source is considered to be equivalent to controlled catchment
Achieving other goals within IUWM	This will negatively impact associated IUWM objectives	No other impacts to IUWM objectives have been identified	Improvements to IUWM objectives are possible but not significant	A small improvement in other IUWM objectives will be achieved	Local or small improvements in other IUWM objectives	Significant impact in widespread amenity and liveability will occur
Environmental Impact	Some increase in environmental impact may occur	No impact on environmental issues	Improvements to environmental performance are possible but not significant	There will be a relatively small increase in environmental performance	A significant increase in a minor environmental issue or a small increase in a major issue will result	A significant improvement in a major environmental issue will result

Table 8.14 Capability to implement IUWM in Ballarat

Criteria	0	1	2	3	4	5
Potential impact on potable water supply	No significant additional water resources will be made available (<5% of forecast potable demand)	Additional water resources up to 20% of the forecast potable demand will be made available	Additional water resources between 20 and 50% of the forecast potable demand will be made available	Additional water resources greater than 50% of the forecast potable demand will be made available	Additional water resources that could potentially meet the forecast potable demand will be made available	Additional water resources in excess of forecast potable demand will be made available
Technical readiness	No current method has been demonstrated.	Technology has been developed but not been implemented	Technology is being tested to prove capability	Technology is known but has not been proven reliable in this configuration	Proven technology but would be seen as new or innovative in this location	Implemented at a number of locations demonstrating widespread capability.
Organisational capability	Water authorities will not accept the change required to enable implementation	A significant change in the organisational structure or expertise would be required and this is very unlikely	Structural change is required to the organisations which will not happen in the short term, but is conceivable in the longer term	Pursuing this is not possible with the current structure, but it is reasonable to consider it may be expected	Some additional resourcing within existing organisational structures may be required	Implementing would be within the expected responsibility of the current organisation

8.5.3.3 Economic assessment of alternative water use options

The following assessment is designed to demonstrate how economic analysis can be combined with the Capability and Social Licence to provide an alternative starting point for the discussion about implementation. Therefore, rather than provide water prices for each option, which may suggest more quantitative analysis had been completed, a comparison to inter-basin transfers is given. This is based on information from studies on costs of alternative water supplies in California (Cooley & Phurisamban, 2016) and Adelaide (Dillon *et al.*, 2014), and the Integrated Water Management Plan for the City of Ballarat (Morgan *et al.*, 2018). While schemes will have different values depending on the circumstances, these are indicative of the relative costs of water adjusted for conditions within Ballarat.

Relative cost of water has been segmented into four categories, higher, similar, lower or significantly lower than inter-basin transfers (Table 6).

Table 8.15 Alternative water supply cost ratings

Alternative Water Supply	Cost Rating	Comment
Stormwater collected locally for non-potable use	Significantly lower	All studies found that capturing and using stormwater locally without requiring treatment is the lowest cost option
Stormwater with Managed Aquifer Recharge for non-potable use	Higher	Ensuring the water is suitable quality for charging to the aquifer and providing distribution for the water to industrial or third pipe schemes has a cost disincentive
Stormwater for potable use – above ground storage	Higher	Providing additional storage for a centralised scheme adds a cost disincentive
Stormwater with Managed Aquifer Recharge for potable supply	Lower	Treatment costs are similar and no additional distribution is required
Rainwater tanks	Lower	No treatment or distribution is required, however the cost of storage is relatively high
Recycled wastewater for non-potable purposes	Higher	Treating the water so it is suitable quality for charging to the aquifer and providing distribution for the water to industrial or third pipe schemes has a cost disincentive
Recycled wastewater for indirect potable use	Similar	Water treatment is required but there are no additional distribution costs
Recycled wastewater for direct potable use	Similar	Some savings may result from not injecting the water to the aquifer, but further transfers to storage are required
Desalination	Higher	High capital, operating and pumping costs
Inter-basin transfers	Similar	-

8.5.4 Strategic Assessment Triangle scores for alternative water supply to Ballarat

Based on the rubrics developed, each of the ten identified alternative water supply opportunities were scored, and a total score produced for the categories, Social Licence, Capability and Economics.

Table 8.16 Alternative water supply social licence and capability ratings

		Social Licence						Capability				Economics
		Community support	Political	Public Health	IUWM	Environment	TOTAL	Water supply	Technical	Organisational	TOTAL	
1	Stormwater collected locally for non-potable use	5	5	5	4	4	23	1	5	5	11	4
2	Stormwater with Managed Aquifer Recharge for non-potable use	4	5	5	3	3	20	2	5	3	10	1
3	Stormwater for potable use – above ground storage	3	3	4	5	2	17	2	4	3	9	1
4	Stormwater with Managed Aquifer Recharge for potable supply	2	3	3	2	3	13	2	4	3	9	3
5	Rainwater tanks	5	5	4	3	3	20	2	5	5	12	3
6	Recycled wastewater for non-potable purposes	4	5	2	1	0	11	3	5	4	12	1
7	Recycled wastewater for indirect potable use	2	3	1	1	0	7	3	5	3	11	2
8	Recycled wastewater for direct potable use	1	2	0	1	0	4	3	4	3	10	2
9	Desalination	3	5	5	1	0	14	5	5	5	15	1
10	Inter-basin transfers	4	5	5	1	1	16	5	5	5	15	2

8.5.5 Opportunity Portfolio Map for alternative water supply to Ballarat

Based on the results of the Strategic Assessment Triangle, the Opportunity Portfolio Map can then be produced. The scaling of the axes is chosen to show a differentiation between

options. The objective is not to produce a definitive answer about which is the 'right' answer, but to enable the conversation regarding the issues with each of the alternatives, and what would need to change, or the barriers involved, with their implementation.

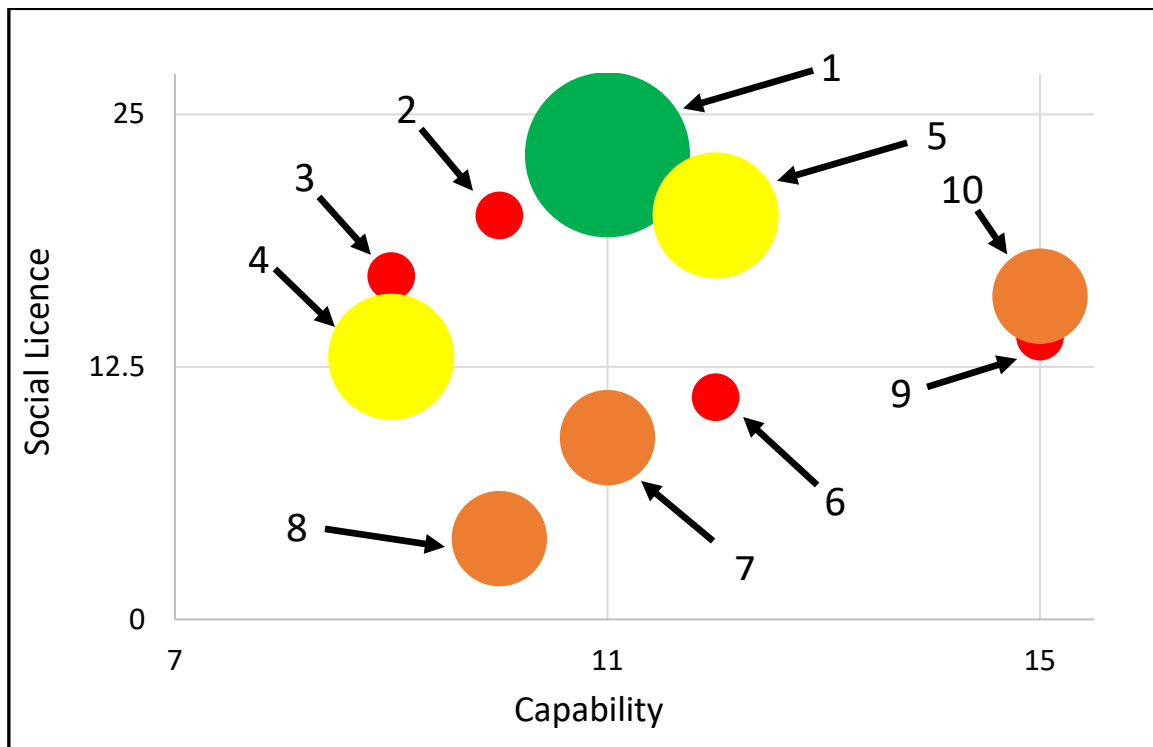
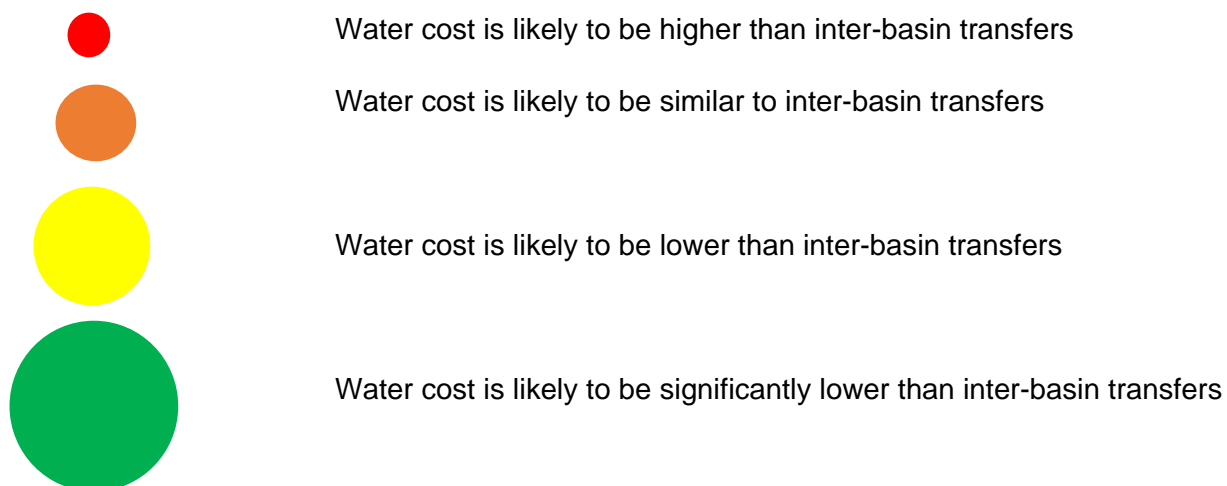


Figure 8.3 – Opportunity Portfolio Map for alternative water supply options to Ballarat



8.5.6 Alternative water supply option assessment

Based on the rating from the Strategic Assessment Triangle, and therefore the position and size of the outcome on the Opportunity portfolio Map, each of the water supply options can

be described using the terminology which is known to be important if change is to be successfully implemented.

Stormwater collected locally for non-potable use – There is high social licence with the community supporting the use of stormwater for public open space irrigation which can produce greener, cooler urban spaces, and this has a low unit water cost due to no need for treatment or distribution. While this can be implemented within the current structures of water authorities, it is not likely to have a significant impact on the overall water supply.

Stormwater with Managed Aquifer Recharge for non-potable use – Water use for non-potable purposes has high acceptance, however the use of the aquifer raises concerns within some sections of the community, and will need additional cross authority co-operation and additional resources to manage. Distribution of water from storage will require additional infrastructure impacting the cost.

Stormwater for potable use with centralised above ground storage – The construction of a dam for storage causes concern regarding the effect on the river, and the capability of managing releases into the future to produce desirable environmental outcomes. However, it has high potential for developing positive public amenity.

Stormwater with Managed Aquifer Recharge for potable supply. Potable water supplies from anything other than a protected catchment cause greater community and political concerns, and will need additional and cross authority support to enable successful implementation, although the economics are favourable as additional distribution is not required.

Rainwater tanks – Collecting rainwater for use within and around the home has high support, and the economics are relatively good with no treatment or distribution required. While it is occurring within the current organisational structures, it has limited capability to impact the total water supply, although this may be higher than many other options.

Recycled wastewater for non-potable purposes – As something occurring within Ballarat currently, it can continue with the current organisational structures, but distribution to suitable end use negatively impacts the capability. While using stormwater has the potential to minimise damage due to peak flows, rivers currently rely on the wastewater stream which will become more highly concentrated. Local stormwater schemes can produce greener, cooler urban spaces, however recycling wastewater has no additional impact other than where it is used, resulting in a lower result for social licence

Recycled wastewater for indirect potable use – The economics are favourable as no additional treatment is required compared to Class A water, however community acceptance is lower and additional resources will be required. Wastewater is 80% of the water supply.

Recycled wastewater for direct potable use – Having no natural, long term buffer between recycled wastewater and the potable supply will further increase resources required and reduce community confidence.

Desalination – Technology that is widely used and can produce essentially unlimited supplies, however concerns regarding the high energy use including additional pumping and concentrated waste reduce the social licence. The cost of desalinated sea-water is currently higher than inter-basin transfers.

Inter-basin transfers – Presented as the base case due to its implementation, it has high capability however the community acceptance is not as high as for local water supplies, and the environmental impact is greater due to pumping.

8.6 Discussion

The barriers preventing widespread adoption of IUWM are of significant interest as increasing demand for water corresponds with limitations of current supplies. However the complexity of the problem can make assessment and visualisation of these barriers difficult, and therefore addressing them becomes less likely. To successfully implement change it has been shown that social licence and capability must exist along with a business case, so the ability to demonstrate those three factors visually can assist the necessary discussion. This is particularly important with alternative water supplies, as one of the key factors identified has been community support.

The use of a rubric to convert a qualitative analysis such as STEEPLE into a quantitative result, as with all multi-criteria decision matrices, is problematic. There are numerous methods and articles regarding multi-criteria decision matrices or similar scoring systems and the scoring of the options within this analysis is open to question. However, this highlights the advantage of a method which utilises a multi-factorial visual tool with regions demonstrating the issues, rather than something which provides a supposedly definitive answer. Within one accessible chart, the concerns with any of the water options considered can be demonstrated. The importance is not in the analysis per-se, but in the discussion about the decision making process.

The ability to demonstrate multi-factorial concerns and to differentiate between available choices stimulates and informs this discussion which then enhances the decision making when undertaking comparative analysis of options. The reality that decisions will alter given time, information and circumstances evolve is also of importance that can be lost when a definitive answer is given.

A desk top study and simple rubric was used to produce the results in this example, however the methods used is not the most important consideration. Detailed analysis feeding into the three factors can be undertaken, and this may adjust results, which will also be specific to location and time. However, the discussion regarding the decision making process in each case needs to consider the multiple issues and barriers, and this framework enables a common method for demonstrating the three criteria identified as important in change implementation.

The assessment of alternative water supply options, all of which may broadly fit within the bounds of IUWM, illustrates that each has its own community, social, regulatory and technical barriers that are complex and contextual. For any of these to be implemented, barriers must be understood so that appropriate actions are taken to address concerns. Demonstrating this at all stages of assessment can assist the process, and the Strategic Assessment Triangle and Opportunity Portfolio Map can do this in an accessible manner, maintaining rigour within the analysis while recognising uncertainty, providing another approach to the analysis and demonstration of complex issues.

8.7 Conclusions

There is an established requirement for assessing multi-criteria problems, and the nature of the numerical comparative techniques that are commonly used results in a lack of transparency regarding the underlying complexity in the reported information and an inability to understand the barriers to implementation for individual options based on different strengths and weaknesses. The Strategic Assessment Triangle and the Opportunity Portfolio Map overcome these issues, and are useful at all stages of assessment, particularly at the early stages when data adequate for a full business case assessment is not yet available. While techniques similar to MCDM's are used in that multiple questions covering a variety of criteria are used to establish a scoring rubric, maintaining the multiple factorial information throughout the process, and the ability to present this information in a readily accessible manner, removes the emphasis on the allocation of weightings. While being quantitative, the matrix allows for an improved understanding of the issues under consideration, and is not as reliant on precise information as other techniques. It can therefore be successfully used at the early stage of a comparative assessment to highlight issues, but can also be used during the final decision making as the information becomes more precise, allowing for uncertainty and change over time.

The Strategic Assessment Triangle and the Opportunity Portfolio Map provide another method for assessing and displaying comparative assessment information, and this enhances the discussion regarding implementation in complex environments. Competing

factors often leads to contested decision making, and a technique which enables multiple criteria to be presented and adjusted can improve the analysis.

9. DISCUSSION

9.1 What are the lessons for water management from this research?

The objective of this thesis as stated in the introduction (Section 1.2) was to investigate the potential for using stormwater to supplement the water supply of a city, and given the apparent benefits, understand of why this does not happen more widely given all the complexities of urbanisation. To achieve this objective the outcomes must inform water management to assist with improved decision making. Key discussion points from the research have been summarised into four themes:

- 1) Urban water use
- 2) Price sensitivity of water demand
- 3) Stormwater as an alternative supply
- 4) Impact of peri-urban development

9.1.1 Urban Water Use

The thesis begins with a discussion on water stress caused by the continuing increase in demand and limits on traditional supplies. However, the water-use in Ballarat peaked in 1980, with the per person use staying constant from some time in the mid 1970's and declining from the mid 1980's (Chapter 3). In Melbourne there has also been a decline in water use, with this occurring over the past 20 years after use peaked in 1998 (Melbourne Water, 2017b). In the United States, domestic water consumption has also shown signs of decline (Dieter *et al.*, 2018), with significant reductions since 2000. While these examples do not suggest that water stress is not a major issue throughout the world, it does demonstrate that urban consumption can be controlled.

The pathways followed by those cities that have achieved a reduction in water use have a similar pattern:

- a. Water is made available through the construction of some central infrastructure such as reservoirs and initial distribution.
- b. The growth of infrastructure and community expectation regarding the availability of water results in it being accessible throughout the city.
- c. The improving economic status and awareness of residents provides the opportunity to install features such as hot water, showers, dishwashers, washing machines and other devices which use water.

- d. The relative cheapness and available water leads to profligate use.
- e. There is a recognition that the continued path of increasing use cannot continue indefinitely.
- f. Efforts are made to reduce the use of water, either through education, technology or economic incentives.
- g. Water use is reduced before stabilising at some lower level.

Although this is a common progression, it is not to suggest that all cities must go through these stages in managing water use, and there is a recognition that the examples are all taken from western societies which flourished economically between the time of water supply installation in the mid 1800's and the end of the 20th century. However, it does typically follow the product life cycle of many goods being introduction, growth, maturity and decline.

The management of water demand of cities will then depend upon the part of the product life cycle in which they are operating. Unlike consumer goods, and cities which were developing 100 years ago, the growth phase must not be allowed to expand indefinitely before controls are introduced, however the controls which are known to work, price, technology and advertising campaigns, can be introduced at any time. These techniques do rely on metering of use which has not been widely implemented in parts of Europe (Werner & Collins, 2012).

The traditional supplies of surface and ground water for potable use are limited and potentially decreasing. Total population and the amount of people living in cities is increasing placing higher demands on the supplies. However, with the use of targets and known management techniques, it is possible to manage the demand of a city, as was clearly shown in Chapter 5 with the Ballarat case study.

9.1.2 Price sensitivity of water demand

A well understood and widely used mechanism for controlling demand of any product is price, and water is no exception. Economic theory shows that increasing the price of water will reduce demand, and the case study from Ballarat was a clear example of this being applied with some success (Chapter 4). However, the price during half the time consumption was reducing was not based upon the volume used, so there was no direct economic incentive. This suggests the mechanism for pricing water may not be as critical as the message sent about the importance of the resource. This would need to be part of a wider campaign regarding the value of water conservation.

As water price increases and campaigns regarding water occurred together in the Ballarat case study, as they inevitably do in many places, the cause and effect cannot be entirely

separated. However, the elasticity of price on external water use of -0.4 closely matched other studies, suggesting this was a clear example of the effectiveness of this strategy. As water pricing and conservation are complimentary, it may not be necessary to differentiate these aspects further.

The case study is an example of the sensitivity of discretionary use to price, and how price has almost no effect on non-discretionary use. While this is not surprising, demonstrating it clearly can assist with establishing this reality with a wider audience. Once water consumption in Ballarat was limited to effectively indoor use only, a further 60% increase in price caused no reduction in use. The ratio of sewage flow to potable water use in a system with separate sewage and stormwater systems was an effective technique that clearly demonstrated the break point between discretionary and non-discretionary use.

The combination of controlled city water use and pricing mechanisms having an effective limit can potentially create difficulties for urban water authorities requiring additional funding to undertake activities, if this money is to be raised from consumers directly. During a growth phase, the additional customers and use will generate an increasing revenue stream. Increasing prices may then be justified as a mechanism for encouraging water saving behaviour. However, once price rises are no longer impacting use, they exist only to generate further revenue, which may be essential to provide the required service, but may not be looked upon so favourably by the customer.

9.1.3 Stormwater as an alternative supply

With the need for additional water supplies and to protect rivers, stormwater use is conceptually attractive. In places where aquifer storage is available, such as Perth and Adelaide in Australia and regions of California, USA, it has proved to be effective. As storage will always be required for significant stormwater use given the intermittent nature of supply, and demand being lowest when availability is highest, Managed Aquifer Recharge overcomes the economic issue of surface storage, as land prices in urban areas create an inherent barrier.

However, this study has shown that the multiple impacts of urbanisation do not inevitably lead to additional water resources being available (Chapter 5). The rainfall/runoff relationship within urban environments has not been widely studied and the complexity of urban hydrology and the changes over time are only beginning to be understood in detail.

In non-urban and unimpaired catchments, which have been the predominant source of water supply for cities, changes to the rainfall/runoff relationship over time and particularly after periods of drought have been documented (Saft *et al.*, 2016), although the reasons for this

occurring are not yet clear. Rather than being seen as a simpler hydrology problem where pervious surfaces are replaced with impervious surfaces, the urban scenario may be represented as the unimpaired catchment with significant land use change overlaid. The non-stationarity of the unimpaired catchment is compounded by multiple extractions, additions and interruptions to surface flow, changes in infiltration and the modification to groundwater. In addition to the well understood increase in flashy stream flow from impervious surfaces, there are impacts from urbanisation which dampen flow. Retarding basins to prevent flooding, dams upstream of cities and treatment plants with relatively constant outflows all reduce the variability of stream flow. The change in the rainfall/runoff relationship over time within urban areas is not well understood.

This is contextual. There will be cases, such as on a uniform, sandy aquifer, where the change in surface flows are well known, or where river flows are dominated by baseflow from snow or glacier melt, where urbanisation is only significant due to localised peak flow increases. This work has highlighted that to utilise stormwater to significantly substitute for the current potable water supply while achieving environmental objectives in downstream rivers, an understanding of the unique urban hydrology is required. It has also demonstrated a technique to quantify the relative size of known impacts of urbanisation (Chapter 5).

9.1.4 Peri-urban development

One aspect of urbanisation that significantly impacted the urban water balance and availability of stormwater as a resource in Ballarat is peri-urban development. Peri-urban areas are not well defined, and are generally considered the transition area between urban and rural zones which can cover hundreds of kilometres from the urban boundary (Webster & Muller, 2009). As urban development accelerates and universally encroach into rural areas, the majority of the research has been on the impact on what was the rural area, or those living within the peri-urban zone which is being rapidly changed.

There is however, a secondary peri-urban development impact. As cities become larger and population density increases, there is a desire amongst some portions of the population for 'greener living'. While the predominant population transfer is from regional areas to the city, there is some migration from urban to rural areas, which in Australia has been referred to as a 'tree change' (Ragusa, 2010) with the attractions including a lower cost of living in an area enabling a rural lifestyle, while still within reach of a city. The impact this can have on the water balance has been calculated for the Ballarat case study (Chapter 5), and previously discussed with regard to similar peri-urban environments (Sinclair Knight Merz, 2004). Water management in these regions can be seen as a microcosm of the issues taking place at a wider scale – the conflict between irrigators, the environment and urban use.

Rural landholders require water for production, and their political interests are represented in Australia by the National Party. In irrigation areas, water rights are separated from land ownership and can be traded and the capture and use of water is controlled. Those moving to these areas for lifestyle reasons may be more aligned to conservation of the natural environment, politically represented by The Greens. Their use is much smaller individually, and water use and storage at this scale is uncontrolled, however the proliferation of small dam storage and the extensive area it covers can substantially impact surface flow.

While there is a recognition that peri-urban development can impact the urban water balance there has been no demonstrated technique for effective control. The Victorian Government introduced legislation in 2011 to require registration of all farm dams (both off stream and on stream), but this was removed in November 2017 for properties less than 8 hectares (20 acres) as part of a wider water management review (DELWP, 2017) which indicated the policy had been ineffectual. Technically, permits are still required for those dams (and other structures) being constructed on stream waterways. Without some action to control the impact of peri-urban development the impact on the surface water flow to rivers can be severe.

9.2 Water monitoring, data availability and IUWM

9.2.1 Monitoring requirements for IUWM

IUWM considers the whole of the water system within a city as an entity and attempts to optimise the whole cycle, rather than individual components as has been done traditionally with separate management of water supply, drainage, sewage and groundwater. To successfully monitor a system, it is necessary to measure all inputs and outputs at the point at which the system boundary is crossed. This implies that to successfully monitor the success of IUWM a water balance assessment framework is required which includes:

- Precipitation on the city and catchment
- Bulk transfers of water into and out of the city
- Water consumption within the city
- Treated wastewater volumes to receiving waterways
- Abstractions from waterways
- Streamflow data for the receiving waterway
- Changes in storage level within the city

- Changes in groundwater storage (recharge and discharge)
- Evapotranspiration

While much of this data may be available, it is rarely collated in a uniform manner for a city. One of the most significant items within the requirements for this water balance is the flow downstream of the city. As demonstrated in the results of this work, the downstream flow enables an assessment of the impacts of urbanisation on the hydrology, therefore measuring the effectiveness of IUWM within a particular catchment. The majority of water monitoring has been established to determine resource availability, and as downstream flow does not meet these criteria, the number of cities with downstream data is very low. In Ballarat, where access to downstream data has been obtained, the monitoring point is 22km from the urban boundary, much further than is desirable if an assessment of the city alone is the objective.

Monitoring on some streams within a city boundary may provide data, although other information for that sub-catchment such as consumption and abstraction is rarely segmented appropriately for this type of analysis. City development is not aligned with water catchments, so the ability to draw a meaningful system boundary appropriate for IUWM is challenging.

9.2.2 Current monitoring

The current status of water monitoring has evolved based on the historical needs of authorities. This could be summarised as

- Long term, strategic information required for water resource planning and water security, e.g. storage levels, rainfall/runoff modelling and climate data.
- Short term, tactical information required for water business operations, e.g. water use, demand, transfers, wastewater and abstractions.

This monitoring enables optimisation of a component within the water system. For example, a water supply authority may have the responsibility to ensure an adequate water supply for their customers at the lowest possible cost. Understanding rainfall and runoff within catchments and streamflow into storage meets these requirements.

There is however, total water system data available. Victorian Water Accounts (DELWP, n.d.-b) provide annual information on water resource availability and complete water balances on the 29 river basins throughout Victoria, Australia. A similar process for completing a water budget has been developed by the United States Geological Survey

(Healy *et al.*, 2007). The information within these balances include rainfall on the catchment and estimated inflow, diversions to urban and other licensed use, an estimate of usage from small dams, evaporation and infiltration and the river outflow from the catchment. The completion of a water balance over a river basin is consistent with the physical reality. However, while this information is required and has proved useful in completing the analysis in this thesis, it does not cover a spatial area appropriate for the ongoing assessment of IUWM.

9.2.3 Required changes

Managing the overall urban water cycle is becoming an accepted method for reducing demand on traditional water supplies and improving urban amenity. If it is to be successful, monitoring will be required for two fundamental reasons.

- To measure the degree of implementation
- To ensure that the system impacts of IUWM are understood.

Water monitoring has evolved over time to suit the needs of water and other authorities, and it could therefore be expected that this will also occur with IUWM. However, if implementation of IUWM is to occur quickly, a concerted effort to increase monitoring may be required. Proper calibration and maintenance regimes for monitoring equipment also needs to be considered. It could be said that the catchment water balance is of greater importance than the city water balance and that additional monitoring for IUWM is superfluous. However, this does not provide information at a local level which is necessary if community wide stormwater schemes are to be encouraged as monitoring must be at the appropriate scale of the impact being measured.

A common platform for water information within a region (country or state for example) would assist significantly with all water monitoring. All information sourced by one authority would then be available for other authorities. As the information is generally in the public domain, this should not provide additional difficulties but would increase efficiency.

The most important stage of monitoring a total system as is the case with IUWM is the definition of system boundaries. To monitor the success of IUWM within a city, the boundary within which the water balance is to take place must be agreed. City boundaries will not follow catchment or sub-catchment boundaries. Following the sub-catchment boundaries has some innate physical logic but would require information such as usage and transfers to be segmented. Alternatively, the city boundary has more administrative sense but will again require transfers to be determined, even though they may be within a sub-catchment.

The outflow from the system is one of the most significant items for overall monitoring – in this case the streamflow downstream of the city. This is currently rarely available. While some streams are monitored within cities, they are often a portion of the overall flow. Downstream monitoring is more often at sub-catchment boundaries rather than located for the purpose of determining the impact of city water management. Appropriate monitoring stations will need to be identified and installed based on the IUWM boundaries previously established.

9.2.4 Enabling the change

Enabling IUWM will require institutional change, and possibly legislative change, as currently there are fragmented statutory responsibilities. As research has identified one success criteria for IUWM implementation being the informal networks across authorities (Rijke *et al.*, 2012), an initial stage may be the creation of enablers working within the existing framework. One consideration would be the determination of IUWM boundaries and once this is achieved the information required for an IUWM water balance can be determined, and all available information sources identified.

This research has identified the benefits to IUWM of downstream flow monitoring, but to enable this funding sources must be identified. The literature suggests that higher cost of WSUD developments has been one barrier to implementation (Brown, 2005), with some developers only pursuing this option when it enables the use of sites that would otherwise be prohibited (Argue & Barton, 2007). As WSUD reduces the need for traditional infrastructure, developer rebates have been proposed. A similar system could be considered for IUWM monitoring. As IUWM provides improved urban amenity the developer is in a position to create additional value. The need for other infrastructure is also reduced as water supply is supplemented and drainage is part of the system design. Future environmental mitigation is also avoided. Assigning a portion of developer and infrastructure funds to IUWM monitoring to ensure its success may lead to the lowest overall system cost. The pursuit of funding possibilities for IUWM monitoring is an area for further research.

9.3 Secondary Data

The digital age has resulted in a massive amount of data being collected and stored, with this increasing all of the time. This data provides opportunities for analysis that can lead to greater understandings and efficiencies. Government organisations around the world generally encourage and enable the collection, storage and access to data. An example of this is the data collection site in the United States, Data.gov stating “...the more accessible,

discoverable, and usable data is, the more impact it can have.” (US Government, 2018). The European Union Open Data Portal has a similar message in that “By providing easy access to data — free of charge — we aim to help you put them to innovative use and unlock their economic potential.” (EU Publishing House, n.d.), while a report for the European Bioinformatics Institute valued the open access data to be twenty times the cost of its provision (Beagrie & Houghton, 2016).

“Data Democracy is the concept of creating a level playing field where we can all access the available data in a timely and equitable way (CeRDI, 2018).” It increases transparency, provides opportunity for review, while enabling greater opportunities for analysis and discovery. This is particularly important for public data that has been collected by government authorities, paid for by taxes and rates. While there is recognition that data access and availability can have real benefit, and data sets from government institutions are more readily available than previously, there are still barriers with data storage, formats, digital literacy and access. Widespread data availability does not equate to knowledge. While data is a pre-requisite, analysis of what is available is of greater importance. Increasing availability and access to data will result in increased analysis, potential for research and improved decision making, ultimately leading to better outcomes for society.

9.3.1 Water information in Victoria

Water management, and therefore water information, is segmented in Victoria, as it is in many parts of the world. DELWP is the custodian of centralised water information which has been used and referenced within the results sections of the thesis, including the Water Measurement Information System and the Victorian Water Register. The BoM have been given responsibility under the 2007 Act for unifying the reporting of water information of water information throughout Australia, in addition to having the primary responsibility for climate information. Catchment management authorities have responsibility for regional waterways, floodplains, drainage and the environmental water reserve. Rural water corporations provide irrigation and stock and domestic water services, while urban water corporations manage treatment, potable supplies and sewerage systems.

Each of these institutions has individual requirements, IT systems, structures, and protocols resulting in little commonality of information in real time. The water corporations are essential services and have commensurate data protection requirements. This includes privacy requirements for customer information as well as restriction of access related to cyber security and terrorism. The work that has commenced at the BoM is a recognition of these barriers to efficiency, including the adoption of international data exchange standards via WaterML (see <https://en.wikipedia.org/wiki/WaterML>). Work has also commenced on an

Intelligent Water Network (Beal & Flynn, 2015), which while its focus is on the introduction of new technology across the industry, this commonality can assist data transfer in the future.

Much of the information use in this thesis was obtained from government reporting such as corporation annual reports. Whether these are available on line or in hardcopy information via archives, formats vary between institutions and over time and must be extracted and transposed manually. Institutional changes over time can also result in information from the previous authority being lost.

While there is more information available than ever before, and much of it is accessible to those who are willing to pursue it, the disparate nature of the information, data platforms and storage protocols remain a barrier to efficient access to the data to enable productive analysis.

9.3.2 Issues with information sharing

Accessible data in a common format leads to improved efficiency and the possibilities of discovery, however, there are risks. Central storage of information “provides hackers with an easy target” (Mulligan & Schwartz, 2000), by providing large quantities of information in a single place. Data sharing from non-government bodies creates the additional complexity of ownership, intellectual property (IP) and responsibility for quality. Data collection and storage has a cost, and those who fund this will require some return or benefit, and may not wish to share the information. Organisations collect information relevant to them for a current purpose and may not be willing to be providing the funding for others to access that information, while centralised storage and common access requires agreed standards. The benefits from the common data standards may not be those with the responsibility of the data custodian, so the additional cost to them must be justified or dispersed.

While peer-review of research is central to the advancement of science, there is some reluctance with open access to data sets. While this may on occasions be related to ownership of data in a similar sense to commercial organisations, there is an additional issue of data misuse. Data requires manipulation prior to use. Gaps must be assessed and filled via alternative sources, outliers removed and bias corrected. This can be misconstrued by those not familiar with the requirements, or who wish to cast doubt upon results as has been the case with the furore about climate data (Fountain, 2017). The ability to understand, analyse and interpret data is the scientist’s *raison d’être*. Access to raw data can result in incorrect conclusions being drawn by those not taking appropriate care, resulting in time and effort being required to counteract the misinterpretations.

While there are efficiencies from common data standards and accessible storage, the cost of developing standards, maintaining data sets and misinterpretation of data can make this appear not worthwhile to the data custodian. The availability of water data has been highlighted as an issue in Australia within the Water Act, 2007, and the development of Water Accounting Standards (Smith *et al.*, 2012). More generally, the access and availability of data is governed by the FAIR principles – Findability, Accessibility, Interoperability and Reusability (Wilkinson, 2016). This is a major area for ongoing research to which this thesis can only the importance.

9.3.3 Using secondary data

No primary data has been collected for this research. While primary data collection is of great importance, this research indicates how understandings may be gained through assessment of existing data. Secondary data can provide the opportunity for an assessment over a longer period than specific sampling regimes. While data may not be collected for the specific reason to be researched and variables not controlled as in a traditional sampling regime, trends that would otherwise not be seen can be identified. For example, aerial photography has been used to identify the increase in farm dams within the Yarrowee River catchment (Chapter 6), and the ratio of sewage flow to potable water supply enabled the estimation of internal and external water use (Chapter 5). The comparison of water price and usage over time was able to demonstrate a clear example of the elasticity of external water use and price, while showing that internal, non-discretionary use was unaffected (Chapter 5). The difficulty in collecting legacy data from a range of sources and archives, while not as efficient as if it was stored in a standardised manner, is relatively simple compared with alternative data collection methods.

To ensure that the data analysis in this thesis is transparent, and that others wishing to understand either the actual result or the methods employed, it is intended that all information will be collated in a form suitable for submission to Research Data Australia, the flagship service of the Australian National Data Service. A DOI will then be minted once that data has been exposed in the metadata catalogue.

9.4 Evolution of Integrated Urban Water Management

Throughout this thesis there has been discussion of the progressive changes to water management. The undeveloped potential for using stormwater to supplement the water supply while improving environmental outcomes has been the theme around which the work has been developed. The first paper (Chapter 3) used the Urban Water Management

Transitions Framework and the Water Sensitive City as a framework for comparison. Potable water supply, sewage and drainage developed sequentially and to some extent, separately. During the second half of the 20th century the environmental consequences of water management decisions and urbanisation became apparent, resulting in improved waste water treatment and new techniques for stormwater management. The need for a broader approach to urban water management is similar to the development of water management more widely.

Integrated Water Resource Management (IWRM), the co-ordinated development of water, land and associated resources, had been popularised at the 'Earth Summit', the United Nations Conference on Environment and Development in 1992, with greater definition being applied over the subsequent years by the Global Water Partnership (Global Water Partnership, 2000). In his assessment, Biswas (2004) reminded us that the concept had been discussed for sixty years but concluded that while it may have been attractive conceptually, it was not particularly helpful operationally. In response Mitchell (2004) suggested the strengths may be more within the realm of strategic and normative planning and management, and that problems with what to include in an 'integrated' approach were a 'classical boundary problem'. In further work (Mitchell, 2005), the problem of inclusion was further assessed, and a distinction was made between comprehensive and integrated to indicate that IWRM focussed on those factors considered of most importance. These issues, the operational difficulties of an integrated system and what to include within the framework, are also reflected in urban water management.

As the shortcomings of traditional water management became apparent, techniques for addressing specific issues were implemented. The development of alternative drainage systems occurred in parallel around the world (Fletcher et al., 2014). Desalinated seawater has become the most widely used water source after traditional surface and groundwater supplies, with some use of wastewater and stormwater. The urban water cycle has been recognised as impacting green space, the heat island effect and liveability, and consideration of all these factors within the urban area led to the development of WSUD (Lloyd, 2001). This movement fits within the broader objective of generally making cities more sustainable, as reflected in Europe by the Aalborg Charter (Sustainable cities platform, 1994), Agenda21 (United Nations, 1992) and The New Charter of Athens (Editrice, 2003).

While the idea of IUWM has been widely considered and aspects implemented, as discussed throughout this thesis, there is a view that there has been inadequate change within water management, reflected in the structure of water management being essentially unchanged over the past thirty years (Brown, 2005; Camilleri & Trowsdale, 2012; Moglia et al., 2011; Roy et al., 2008). Analysis of the multi-level perspectives which must align if change is to result, suggests that conditions are conducive at both the macro and micro level, with broad

recognition of the need for change and development of the appropriate tools, but at the mid, socio-technical or socio-political level there is difficulties (Patouillard & Forest, 2011). This is consistent with the research suggesting institutional resistance is the greatest barrier to change (Brown, 2005; Floyd et al., 2014; Rijke et al., 2012; Roy et al., 2008).

In the seminal work, 'The structure of scientific revolutions', Kuhn (1970) identifies that a revolutionary change in understanding requires a paradigm shift in thinking. Once an anomaly is determined to pose sufficient difficulties to the current theory, it is not uncommon for multiple groups to work on the problem and concurrently identify solutions, often similar in nature. Development of alternative stormwater management techniques, LIDs in the United States, SuDS in the United Kingdom and WSUD in Australia, fits this pattern (Fletcher et al., 2014). Once the alternative view has been proposed there is resistance from those embedded within the previous system as it has proved adequate until now, and the expertise developed is now brought into question. The testing of the new paradigm can then result in an acceptance of the new perspective, or absorption of additional information into, and adjustment of the framework of the existing theory. It is known that changing the paradigm provides much greater leverage for change than interventions such as subsidies, providing better information or rule changes (Meadows, 1997). However, the presence of anomalies, the search for a better solution and desire for change does not necessarily determine that a paradigm shift has occurred – it may be the evolution of existing thinking, or what Kuhn calls normal science.

Potable water supply and sewage being a component of a larger system is obvious. It is the consideration of which factors to include in managing these that could be considered revolutionary. Alternatively, it could be said that the boundaries of water management have continually changed to include things of importance. For example, in Ballarat the original water supply provided potable water to a growing community, while the reservoir mitigated flooding which was a major issue. The sewerage system followed fifty years later to improve hygiene and efficiency. Another forty years passed before upgraded treatment plants provided the performance that was recognised as being necessary to maintain environmental conditions. A requirement for alternative supplies during the Millennium Drought required encouragement of localised systems such as rainwater tanks for external water use, and inter-basin transfers to supplement the centralised supply. These changes have all developed within the existing structure of water authorities but can be considered to have altered the boundary of urban water management.

While IUWM has been identified as requiring a new authority or cross-institutional arrangements, in Victoria a multi-authority integrated water management plan is under development (see <https://www.water.vic.gov.au/liveable/resilient-and-liveable-cities-and->

[towns/iwm-framework](#)). This suggests that authorities may be able to evolve to meet the changing needs.

Similar stories of development based on the specific local conditions could be told in a variety of cities around Australia and the world. Adelaide, drier and hotter than other major cities in Australia with a subsequent issue of water supply, uses Managed Aquifer Recharge to store stormwater for re-use for non-potable purposes (DEWNR, 2017). Perth, where reduced rainfall and higher temperatures has resulted in runoff to reservoirs reducing to less than 10% of that captured in the 1970's, can now provide all potable water supplies from desalination and groundwater, in part due to the sandy soil aquifer (Water Corporation, 2013). California has also implemented a scheme for diverting stormwater to the aquifer used for potable supply (Scanlon et al., 2016). There are now over 50 cities throughout the world using recycled sewage to supplement water supplies (Burgess et al., 2015). Most of these use an indirect method, where the recycled water is injected upstream of an environmental buffer such as a river or aquifer, however there are a number of direct recycling systems also, the oldest of which has been operating in Namibia since 1968. This is not simply a third world solution, with Singapore's NEWater (Lee & Tan, 2016) and over twenty schemes in the USA (Burgess et al., 2015) being evidence that in the right circumstances, recycled sewage for potable water is an acceptable and viable option. The impact of green spaces on the heat island effect, part of the holistic nature and improved amenity associated with IUWM, is becoming well understood (Qiu et al., 2017), leading to increased development of tree covered buildings or vertical forests (Carter, 2017).

It is unclear whether these examples indicate whether there is a significant change in the method of urban water management, cities taking the most appropriate action according to specific circumstances, or they are individual examples proving the more general rule that water management has not changed in any substantial way. The language of urban water management is certainly changing. The use of terms such Water Sensitive City, integrated water management, best practice stormwater management, Water Sensitive Urban Design and other terms associated with significant change is now ubiquitous. However, the change in use of WSUD, from its conception as a total system understanding of urban water, to the more commonly applied definition of alternative storm water management indicates how the use of these terms does not imply significant change. In this thesis, IUWM has been used to describe a comprehensive system approach, however to some it may simply indicate the cooperation between different urban water authorities.

Evolutionary change is obviously capable of producing dramatic variation given enough time, and the management of water is no exception. The need for revolution is therefore predicated on whether the rate of change is adequate to deliver the required outcome. It seems pertinent at this point to remember the words of Charles Lindblom in his work on

incrementalism, which he clearly stated was not a case for conservatism or slow change, that development is 'The science of muddling through' (Lindblom, 1959, 1979).

Whether the change in water management is revolutionary or evolutionary, a change of paradigm or an example of incrementalism, a new approach to water management or continued adjustments along the pathway, the assumptions about urban water management must be tested. This thesis has demonstrated techniques for testing a number of the assumptions about urban water management, namely:

- The increasing demand due to urbanisation;
- Efficacy of price to manage use;
- Importance of price mechanism on use;
- Increased annual flow downstream of a growing city;
- It has developed a number of techniques to assist with this testing of assumptions;
- The use of sewage flow to monitor indoor water use;
- Linking an annual water balance with catchment runoff modelling to partition river flow;
- The use of legacy data to indicate groundwater impact; and
- The Strategic Assessment Triangle to understand and visualise relative barriers to change.

One of the tenets of IUWM, that increased impervious surfaces in urban areas will lead to increased downstream flow, has been found in this thesis to be a simplification which does not account for the complex and contextual nature of the urban water cycle. Urban water management responds to the unique needs and circumstances of a city. The development pathway is not smooth or uniform. While changes may appear revolutionary, when placed in the context of water management over a long period, they may be seen as the continued response to the changing needs of the community.

Urban water management will continue to evolve and assumptions will need to be tested and proved if unintended consequences of IUWM implementation are to be avoided.

10. CONCLUSIONS

At the outset of this thesis, five research questions were identified. Work has been done to investigate and answer each of these questions with many useful outcomes found and described in the various chapters of this thesis. This chapter summarises the most salient outcomes for each of the research questions.

1. Does the long-term development of water management within a city provide insight into what drives decisions, therefore informing future progress?

Reviewing the changing water management arrangements of a city by taking a long term historical perspective has revealed that decisions are usually made based on the unique circumstances and local conditions faced. While at a macro scale there are similarities between cities in the phases of water management, differences do occur in timing and the specific choices made. This responsiveness to requirements and the resultant changes over a long period suggest that an evolutionary model is a better description of water management than a revolutionary one. While change is and will continue to be necessary, the history of water management suggests that there will be continued evolutionary responses to the pressures and requirements to achieve an acceptable outcome.

2. Can the drivers of water use be adequately determined from a community wide, historical analysis such that future regulatory decisions can be informed?

The sustained and continuous reduction in water use over thirty year period for the case study of Ballarat is a demonstration of what can be achieved with appropriate policies, incentives and education. The correlation between water price and outdoor, discretionary use, while not a unique finding, is a clear example of both the value and limitations of economic incentives for impacting water use. Price signals will result in modifications to water use behaviour. However, contrary to the classical economic model, a volume based 'user pays' price mechanism may not be as influential. The finding from this research suggests water price, particularly as a water bills are received intermittently (often months apart) and not at the time of use, may encourage and reinforce other water saving measures. Once a threshold of water use has been achieved, further price increases may have no additional effect.

3. Will assessment of the long-term streamflow of a river, combined with an urban water balance of the catchment, enable the identification of additional stormwater flow due to urbanisation, in excess of the natural flow?

A method for combining an annual city water balance with the modelling of other impacts on river flow such as farm dams, rainwater tanks and changes to baseflow has shown that the increase in flow resulting from greater impervious surface areas has been outweighed, hidden, or completely entangled with other variations occurring in the catchment. This result is not unique to the Ballarat case study as it has also been shown in other catchments, including that of a much larger and more densely populated urban area. Therefore, one of the tenet's of IUWM that increasing imperviousness will lead to greater streamflow which can be exploited as an alternative resource, must be approached with caution. Urban hydrology is vastly more complex than this idea suggests, and consideration must be given to the total catchment and multiple areas of influence when determining water resources.

Other conclusions gleaned from the water balance and associate modelling work are that:

- understanding the potential of IUWM and the success of implementation requires sufficient hydrologic monitoring, and this research has shown that flow monitoring downstream of urban centres is an essential component of this.
- sewer flow monitoring was used to provide an estimation of internal water use on a community wide scale for historical data. Where a separate black sewer exists, this technique can be readily applied to gain an understanding of the long term trends of internal and external domestic water use.
- peri-urban development surrounding a city can have a significant impact on surface water flow, and as small farm dams are largely unregulated in Australia, there is currently no mechanism for monitoring or controlling this.

4. Can the impact of urbanisation on groundwater be identified (i.e. trends quantified or qualified) from the city's legacy data or any available data sources, or models?

Understanding long term groundwater behaviour was found to be an important component of understanding the regional scale urban catchment water balance. However, data was not readily available or in an immediately useful form. This meant that a range of data, including from non-traditional sources, was necessary to form an understanding of the changes to groundwater. While the techniques used may not be applicable to all catchments, the results obtained did lead to a significantly deeper understanding of the groundwater resource over time without the need for an expensive monitoring program. Some of the more

unconventional methods used also highlights more broadly that a forensic and interdisciplinary approach to historical data collection, particularly if collated and distributed in a standardised manner, can assist with hydrologic analysis and lead to further understanding.

5. *Is it possible to establish a comparative analysis technique that accounts for the uncertainty of information which changes over time, maintains intellectual rigour and is understandable and easily presented?*

Identifying alternative options for water supply often forms part of IUWM decision making and this is where objective comparative analysis methods become very useful. Comparative analyses in complex decisions can be achieved by the use of techniques such as multi-criteria decision-making (MCDM), but these simplify the answer to a single result, leading to the 'best' answer. The Strategic Assessment Triangle used in the current research has similarities to MCDM, however, retains three factors known to be important in the success of change implementation, being value, social licence and capability. Opportunities are therefore presented with an understanding of the caveats, and decisions can be demonstrated and made with an understanding of the uncertainty and limitations. This provides another tool in the pursuit of improved decision making in complex situations and is concluded to provide great potential to IUWM practitioners.

Broadly speaking, while the benefits of using stormwater to supplement the water supply of a city may seem apparent, a primary conclusion from this current research is that IUWM remains a complex disciplinary area and that solutions are very contextual in application. The assumption that increased urbanisation will logically lead to higher volumes of runoff and associated streamflow has been challenged in this thesis. Monitoring runoff and streamflows downstream of urban centres should become an essential and requisite requirement to monitor progress of IUWM implementation and to ensure unexpected consequences do not occur from well-intentioned activities. Water management has clearly evolved over time to meet continually changing needs of communities and this must be allowed to continue happening, including and commensurate with consumer acceptance of environmental impact and regulatory and organisational implications in the decision making regarding supplementary water supplies.

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