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Dual-duty Rainwater Harvesting: Water Supply and Urban Stream Restoration

Dissertation submitted by

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ABSTRACT

An exciting epoch is before us where we are focused on transforming urban living to a higher symbiosis with nature. For now, and looking over the immediate horizon, the pursuit is for water sensitive cities with green spaces which encourage a modern lifestyle that is considerate of, connected with and dependent on the natural environment. Practical realisation of this vision is perpetuated by innovations in water sensitive urban design (WSUD). The main objective is to capture, treat and use stormwater at its source, of which rainwater harvesting is fundamental.

Rainwater harvesting is well-known as a decentralised water supply alternative or supplement to the centralised water supply services of municipalities. The majority of design and assessment of rainwater tanks is focused on the reliability of supply. Additionally, rainwater tanks can significantly improve urban hydrology by capturing, consuming and effectively removing excess urban runoff. In this dissertation, a new approach is introduced to assess the combined outcomes of rainwater tanks. Dual-duty rainwater tanks are designed to restore degraded aspects of urban hydrology which stream ecosystems are particularly vulnerable to, while providing an alternate water supply.

The dual-duty performance framework is applied to examine the implications of enabling environmental flows from rainwater tanks. Research questions are explored: will environmental flows improve dual-duty performance; are adaptive approaches for managing environmental flow superior to a fixed leaking approach; to what extent do environmental flows diminish water supply; can rainwater tanks significantly improve urban stream hydrology in isolation to WSUD or other stormwater management initiatives; and what are the realistic expectations of dual-duty performance across the spectrum of urban residential living in Australia.

To answer these questions, a mass-balance rainwater tank simulator UrbanTank © was created and alternate storage arrangements and operating conditions were studied including the *conventional tank*, where the sole purpose is to supply rainwater to households and environmental flows do not occur; *the leaking tank*, which trickle-releases environmental flow from a virtual chamber of fixed volume; and *the adaptive tank* where environmental flow storage is actively regulated by the severity of rainfall statistics, rainfall forecasts and/or a combination of both controls.

Also, to qualify simulation results outdoor water use was linked to climatic indices of daily rainfall and daily maximum temperature. Rainwater yield estimates were verified by independent field measurements, simulation and statistical analyses throughout Australia. To allow a comparative assessment of all tank alternatives, a method was developed to supplement the limited duration of rainfall forecast archives.

The results demonstrate environmental flows, regardless of the method of operation, significantly improved dual-duty performance; the increasing complexity of adaptive approaches for managing environmental flows was not justified by a significant improvement in dual-duty performance over the simpler leaking tank arrangement; when enabling environmental flows the water supply independence dropped by a marginal 2% while the environmental benefits increased by 33%; the leaking tank was able to achieve on average a 90% compliance with natural hydrology measured by a simplified version of the environmental benefit index, which demonstrates rainwater tank can be used in isolation to WSUD or other stormwater management initiatives; and results from leaking tanks are encouraging over the breadth of simulation scenarios studied.

The dissertation concludes by establishing a relationship between dimensionless fractions and the key performance metrics of supply independence and environmental benefit index. These relationships facilitate rapid assessment of the dual-duty performance of conventional and leaking rainwater tanks across the spectrum of urban residential living. Rapid estimates are based on rainfall statistics, which can be potentially determined at any location in Australia and for similar climates elsewhere; and the scope of parameters studied which comprise roof area

($100\ m^2$ to $200\ m^2$), tank volume (2.5 kL to 7.5 kL) and annual rainwater demand (44 kL/y to 176 kL/y).

This dissertation has introduced a dual-duty framework for the design and assessment of rainwater tanks with a focus on minimising the degradation and demand municipalities place on contiguous water resources. These contributions to research have broadening our scientific knowledge and it is hoped the outcomes will expedite the promotion of water sensitive cities.

CERTIFICATION OF DISSERTATION

I certify that the ideas, experimental work, results, analyses and conclusions reported in this dissertation are entirely my own effort, except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award, except where otherwise acknowledged.

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Signature of Candidate Date

ENDORSEMENT

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Signature of Principal Supervisor Date

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Signature of Associate Supervisor Date

ACKNOWLEDGEMENTS

At the start of this venture, Queensland and many parts of Australia were experiencing water shortages from the recent Millennium Drought. This soon changed with the major wide-spread flooding of 2010-2011. Now, Australia Day 2013, we are experiencing the worst flood in recorded history in Bundaberg and again, major wide-spread flooding in eastern states. While not directly related to the technical development of this dissertation, foremost, I would like to thank everyone who kept us safe and informed with flood forecasts, and assisted in the recovery from these catastrophic events.

Only now, as I prepare my final draft, can I truly comprehend the commitment that a dissertation deserves. This commitment reaches far beyond myself, beyond those generous people who have contributed in a technical capacity, and extends to those dearest to me.

I wholeheartedly acknowledge Kathryn, my dear wife, for her support, understanding, encouragement and bravery in trusting me with what has been an enlightening, stressful and very challenging three-year research venture. I acknowledge my beautiful children Josh (6) and Anneliese (4), who have witnessed the entire journey and Katelyn (22 months), who loves helping her Daddy work. Kathryn's and my parents have also assisted by caring for the children while I have attended conferences, workshops, networking functions and training seminars.

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I would like to acknowledge the scholarships which were essential for this venture: from USQ an Australian Postgraduate Award, Faculty of Engineering and Surveying Postgraduate Scholarship and a position in the Australian Centre for Sustainable Catchments; jointly funded by USQ and Griffith University Brisbane, a postgraduate summer 2009 research scholarship at the National Climate Change Adaptation Research Facility; from the University of Sydney two scholarships to participate in the 2011 and 2012 Australia-Korea Next Generation Leaders Program – Establishing ongoing collaboration in water resources management; and jointly funded by the International Water Association and the Universiti of Teknologi Malaysia, a Young Researchers Scholarship to participate in the inaugural IWA Publications Writing Workshop.

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Finally, I would like to acknowledge the anonymous examiners whose constructive comments improved the dissertation in many areas. Also, they have left me with many considerations for further research.

ASSOCIATED PUBLICATIONS

Taylor, B.A. 2010, Extension of Taylor’s Hyetology Index (THI) – Increasing the accuracy of national rainwater harvesting reliability estimates, Report to the National Climate Change Adaptation Research Facility - Water Resources and Freshwater Biodiversity Network, Brisbane, Australia.

Taylor, B.A. 2011, 'Approaching water sensitive cities with adaptive rainwater diversion', paper presented to the *Stormwater Industry Association of Queensland state Conference - Achieving multiple outcomes, a time to reflect*, Surfers Paradise, Australia, 25-27 May 2011.

Taylor, B.A. 2011[a & b], 'Rapid estimation of rainwater yield throughout Australia and review of Queensland rainwater harvesting operating policy', paper presented to the *Escaping silos SSEE 2011 international conference*, Brisbane, Australia, 24-26 October 2011.

Taylor, B.A. 2012c, 'Predicting normalised monthly patterns of domestic external water demand using rainfall and temperature data', *Water Science & Technology: Water supply*, vol. 12, no. 2, pp. 168-178.

Taylor, B.A. 2012, 'Emulating pre-urban initial rainfall losses and restoring baseflow with rainwater harvesting, paper presented to the *7th International Conference on Water Sensitive Urban Design*, Melbourne, Australia, 21-23 February 2012.

Taylor, B.A. 2012, 'Enhancing rainwater harvesting with short-term rainfall forecasts in water sensitive cities', paper presented to the *OZWater12 conference - Sharing knowledge, planning the future*, Sydney, Australia, 8-10 May 2012.

Note that accents denote awards subsequently mentioned.

OTHER ASSOCIATED PRESENTATIONS

Taylor, B.A. 2010, 'Enhancing the performance of domestic rainwater systems - National targets and informative metrics for current and future climate states', poster presented at *the International climate change adaptation conference*, Gold Coast, Australia, 29th June - 1st July 2010.

Taylor, B.A. 2010, 'Enhancing the accuracy, consistency and relevance of sizing rainwater tanks throughout Queensland', presented to the *Central Regional Engineering Conference*, Bundaberg, Australia, 31st July 2010.

Taylor, B.A. 2011, 'Integrating rainwater systems to increase yield and promote stormwater management in water sensitive cities', presented to the *Stormwater Industry Association of Queensland: technical event*, Brisbane, Australia, 27th October 2011.

Taylor, B.A. 2011[c], 'Opportunities to enhance rainwater systems in urban Australia and South Korea', presented to the *Next Generation Leaders Program*, Seoul, Republic of Korea, December 2011.

Taylor, B.A. 2012[d], 'Deriving synthetic rainfall forecasts in diverse climates: Towards long-term analysis of reservoirs', presented to the *International Publications Workshop*, Johor Bahru, Malaysia, March 2012.

Taylor, B.A. 2012[e], 'Urban rainwater harvesting in Australia', presented to the *Korean 2012 delegation of the Next Generation Leaders Program*, Sydney, November 2012.

Note that publications and presentations are linked to respective chapters in the dissertation introduction.

ASSOCIATED AWARDS

[a] 2009 Queensland student research of the year concerning sustainable environmental engineering, awarded by Engineers Australia - Society for Sustainability and Environmental Engineering.

[b] 2010 National Student Environmental Engineering and Sustainability Prize awarded by Engineers Australia - Society for Sustainability and Environmental Engineering.

[c] 2011 Next Generation Leaders Program - Scholarship from the International Leaders Program of Sydney University to participate in an Australian delegation of 10 potential leaders in the field of sustainable water resources management. The delegation travelled to the Republic of Korea for 12 days in December 2011 and networked with Korean counterparts, established industry relations between our nations and is now pursuing ongoing research collaboration.

[d] 2012 International Publications Workshop - Scholarship from the International Water Association and Universiti of Technologi Malaysia to participate in an exclusive technical writing workshop offered to 30 international young water professionals in March 2012.

[e] 2012 Next Generation Leaders Program - Scholarship from the International Leaders Program of Sydney University to participate as a 2011 alumni representative in the Koran delegation tour of water resources industries in NSW, ACT and SA in November 2012.

NOMENCLATURE

Abbreviations

Abbreviation	Description
A	Connected roof area
ANN	Artificial neural network
ARI	Average recurrence interval
BASIX	Building sustainability index
BMC	Behavioural - Monte Carlo synthetic rainfall forecast model
BoM	Australian Bureau of Meteorology
BoS	Australian Bureau of Statistics
d.f.	Degrees of freedom used in statistical analysis
DF	Dimensionless discharge fraction
DW	Durban-Watson statistic of serial correlation of residuals
EBI	Environmental benefit index
EF	Environmental flow
FF	First flush
FFI	Flow frequency sub-index
FVI	Filtered flow volume sub-index
g	Skewness of data
GSS	Gilbert skill score
H	Total rainwater harvest
IW	Import water
MSE	Mean sum of residual error
MUSIC	Model for Urban Stormwater Improvement Conceptualisation
NWC	National Water Commission
O	Rainwater system overflow
p	Statistical significance of prediction
P	Precipitation

PIASA	Probable initial air space available
PMC	Parsimonious - Monte Carlo synthetic rainfall forecast model
PURRS	Probabilistic urban rainfall and wastewater reuse simulator
PVC	Poly vinyl chloride
PYI	Precipitation yield index
R	Runoff
R^2	Coefficient of determination regression statistic
RRL	Rainfall-runoff losses
RS	Rainfall sensitivity parameter
RSD	Rainfall storage drain model
Rsk	Ratio of skewness
Rmu	Ration of mean values
SEQ	South-East Queensland
SF	Dimensionless storage fraction
SI	Supply independence
TT	Temperature threshold parameter
UQV	Urban quality and volume model
VRI	Volume reduction sub-index
VU	Volumetric utility
WSUD	Water sensitive urban design
Y	Rainwater yield
χ^2	Chi-squared regression statistic

Parameters

Symbol	Parameter	Units
A	Connected roof area	m^2
A_c	Catchment area per downpipe	m^2
A_e	Effective cross-sectional area of gutter	mm^2
a	Duration factor in the dimensionless storage fraction	days
b	Volume limiting factor in the dimensionless storage fraction	kL
CN	Correct negative dichotomous forecast	-
CR_r	Coefficient of runoff for roof catchment	-
c	Regression calibration factor in storage and discharge dimensionless fractions	-
d	Regression calibration factor in discharge dimensionless fraction	-
DC_d	External water demand condition for day *d*	-
DF	Dimensionless discharge fraction used to rapidly determine the environmental benefit index	
D_p	Days with precipitation above catchment abstraction	days
D_r	Average annual rainwater demand	kL
D_t	Average annual total household water demand	kL
D_{total}	Total number of days in time-series	days
D_{re}	Average annual household external rainwater demand	kL
D_{ff}	Depth of first flush diversion	mm/d
D_{il}	Depth of initial loss from roof surface	mm/d
E	Roof evaporation	mm/6min
e	The number of random forecast hits expected due to chance	-
EBI	Environmental benefit index	-
E_d	Environmental flow chamber storage percentage of total tank volume for the forecast control signal for day *d*	-
E_{dc}	Environmental flow chamber storage percentage of total tank volume for the combined signal from rainfall statists and forecasts for day *d*	-
EDI_d	External water demand index for day *d*	nil
EF	Average annual environmental flow from rainwater tanks	kL
E_m	Environmental flow chamber storage percentage of total tank volume for rainfall statistics for month *m*	-

FA	False alarm in dichotomous forecast	-
F_{6d}	The six day mean predicted rainfall with a two day horizon	mm/d
$F_{BMC.d}$	The mean six day synthetic rainfall forecast for day *d* from the behavioural - Monte Carlo method	mm/d
FF	First flush discharge	kL
$F_{Gau.d}$	The mean six day synthetic rainfall forecast for day *d* from the Gaussian distribution method	mm/d
FFI	Flow-frequency sub-index	-
F_e	Extreme daily rainfall forecast threshold	mm/d
F_{pluv}	Daily downscaled rainfall prediction at the targeted pluviograph observation site	mm/d
$F_{PMC.d}$	The mean six day synthetic rainfall forecast for day *d* from the percentage error Monte Carlo method	mm/d
F_t	Six day mean trigger threshold for acting on rainfall forecasts	mm/d
FV_{forest}	Unit area filtered flow volume from forested catchments	L/y
FVI	Filtered flow volume sub-index	-
$FV_{pasture}$	Unit area filtered flow volume from pastured catchments	L/y/m^2
FV_t	Unit area filtered flow volume from rainwater tank	L/y/m^2
GSS	Gilbert skill score of rainfall forecasts	-
GSS_h	Gilbert skill score of high frequency sub-sample period of rainfall forecasts	-
GSS_l	Gilbert skill score of low frequency sub-sample period of rainfall forecasts	-
G_{hc}	Gutter hydraulic capacity	L/s
H	Hit in dichotomous forecast	-
IW	Average annual imported water	kL
M	Linear regression gradient of rainfall observation and forecasts	-
MI	Miss in dichotomous forecast	-
MO_{max}	Maximum model output	*varies*
MO_{min}	Minimum model output	*varies*
N_{dp}	Number of connected downpipes	-
n	Number of elements in time-series data	-
O	Average annual system overflow	kL
P_{cap}	Capped daily precipitation	mm

P_d	Daily precipitation observation for day *d*	mm
P_{EF}	Percentage of total tank volume allocated to the environmental flow chamber	%
P_{max}	Daily precipitation maximum threshold	mm
P_{sum}	Summer precipitation	mm
P_{win}	Winter precipitation	mm
PYI	Precipitation yield index	m
Q_{il}	Initial loss rate	L/6min
Q_r	Discharge from roof catchment	L/6min
R	Combined discharge from connected gutters	L/6min
R_d	Daily roof runoff	kL
r	Six day mean rainfall	mm/d
R_n	Number of runoff days per annum from a natural catchment	-
R_{pd}	Ratio of precipitation days each year	-
R_{ps}	Ratio of precipitation seasonality	-
R_t	Number of runoff days per annum from the rainwater tank	-
R_u	Number of runoff days per annum from an urbanised catchment	-
RC_{forest}	Runoff coefficient from a forested catchment	-
RC_i	Runoff coefficient from an impervious catchment	-
$RC_{pasture}$	Runoff coefficient from a pastured catchment	-
RDI_m	Mean monthly rain day index for month *m*	-
RI_d	Unit-normalised daily rainfall index	nil
RS	Rainfall sensitivity calibration factor for outdoor water use model	mm
SF	Dimensionless storage fraction used to rapidly determine supply independence	-
S_n	Stored rainwater at model interval *n*	kL
SI	Average annual supply independence	-
SSI_i	Standardised sensitivity index for parameter *i*	-
T_d	Maximum daily temperature observed for day *d*	°C
TT	Maximum daily temperature threshold	°C
TI_d	Unit-normalised daily maximum temperature index for day *d*	nil
VRI	Volume reduction sub-index	-
VU	Average annual volumetric utility	-

V_c	Volume of water harvest from a rainwater tank or lost through roof evaporation	kL/y
V_{EF}	Volume of the environmental flow chamber in leaking and adaptive rainwater tanks	kL
V_e	Excess runoff volume generated by impervious surfaces	kL/y
V_t	Total tank volume	kL
V_{WS}	Volume of the water supply chamber in leaking and adaptive rainwater tanks	kL
W_{EB}	Priority weighting of the environmental benefit in the volumetric utility metric	-
W_{SI}	Priority weighting of supply independence in the volumetric utility metric	-
X_t	Element value at time or sequence number t	-
XI_t	Unit normalised transformed value (index)	nil
Y	Rainwater yield	L/hour
ΔMO_i	Proportional change in model output for parameter *i*	-
ΔP_{ai}	Parameter change of adopted values of parameter *i*	*varies*
ΔP_{di}	Range of parameter domain for parameter *i*	*varies*
ΔP_i	Parameter change index for parameter *i*	-
Δx	Longitudinal difference between the pluviograph station and the rainfall forecast grid point west	°*E*
Δy	Latitudinal difference between the pluviograph station and the rainfall forecast grid point south	°*S*
α	Mean value adjustment coefficient for generating synthetic rainfall forecast data	-
β	Forecast residual scalar	d/mm
γ	Forecast skill adjustment constant	mm/d
ε	Six day mean gridded rainfall forecast residuals	mm/d
ε_n	Normally distributed forecast residuals	mm/d
μ	Mean value of rainfall forecast residuals	mm/d
σ	Standard deviation of rainfall forecast residuals	mm/d
σ	Standard deviation of rainfall forecast residuals	mm/d
σ_R	Standard deviation of daily rainfall	mm/d
σ_T	Standard deviation of daily maximum temperature	°C
ω	Percentage error of rainfall forecast residuals	-

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Chapter 1 Introduction

Dual-duty rainwater tanks are designed to provide an alternate water supply while restoring aspects of natural steam hydrology to urban catchments. This dissertation explores how to measure dual-duty performance, together with types of storage arrangements and operating practices which promote the dual-duty benefits.

1.1 Overview

The practice of intercepting, storing and consuming runoff from anthropogenic catchments has origins preceding 2000 BC (Evenari 1961), with many chronicling the development of rainwater harvesting (Roebuck 2007; Ward 2010). However, in our more recent past, we had all but replaced decentralised rainwater harvesting with massive centralised systems for collection, containment, treatment and delivery of potable water to meet our cities' universal needs, regardless of the intended end use.

Recently, the operation of water supply systems have faced scrutiny from public and political interests, which were driven by the combined effects of water shortages, the paradigm shift to sustainable practices and the undisputable evidence of climate change (IPCC 2007), a phenomenon they are particularly vulnerable to (Coombes & Barry 2008b; Howard *et al.* 2010). Furthermore, management of water resources is now a global issue, with water security regarded as the challenge of the 21st century by many political and scientific institutions (UN 2010). This attention has dramatically increased community awareness of water as a valuable commodity. As such, society is restless and independently seeking water security by supplementing with rainwater where opportunities exist, often when the economics appear to be unfavourable (White 2009).

Now (early 2013), the rainwater tank is commonplace and characteristic of urban water resources management, with recent surveys of 26 % (1.1 million) households in capital cities adopting rainwater as a supplementary water supply in Australia (BoS 2010b). Their contribution has mitigated municipal water demand and alleviated water scarcity concerns with water savings reported of at least 20% for the average sized participating Sydney household (Ferguson 2011). Adoption of rainwater tanks is steadily increasing with an 8% rise from 2007 to 2010, which is largely attributed to the community desires to save municipal water and to be independent from restrictions of its use (White 2009), together with regulations by building authorities (BASIX 2010) or planning controls (BoS 2010b) and the moral implications to do something for the environment.

But not all authorities appreciate the pertinence of rainwater tanks in urban water security strategies. The Queensland Government recently sidelined their long-term strategy to include rainwater harvesting in water security plans for South-East

Queensland (NRMW 2006) by abolishing their mandate for rainwater tanks with new residential (QDIP 2007a) and commercial premises (QDIP 2007b). This position is somewhat justified by their pursuit of affordable development. This decision has coincided with the fifth anniversary of alarmingly low water storages for Brisbane, such as 13.9% in Wivenhoe Dam during August 2007 (Seqwater 2012). Moreover, looking to the immediate future, rainfall in this region is highly influence by the El Niño - La Nina southern oscillation, which has recently entered the El Niño phase: a period with increasing probability that Eastern Australia will be dryer than normal (BoM 2012f). The minority views of the Queensland Government on rainwater harvesting could be rather unfortunate for the people of Queensland and could be counterproductive for promoting Brisbane as a water sensitive city (BCC 2010).

With a broader perspective, rainwater harvesting is widely found, studied and supported in residential areas throughout Australia (Coombes & Kuczera 2003; Beal *et al.* 2012) and many other countries including the UK (Fewkes 2004), Sweden (Villarreal & Dixon 2005), Brazil (Ghisi 2006), New Zealand (Vale & Ghosh 2006), USA (Jones et al. 2009), South Africa (Kahinda et al. 2007) and South Korea (Kim & Yoo 2009), to mention a few. The essential role and broad potential of rainwater harvesting in challenging settings is demonstrated by these and other studies, such as, arid regions of China (Zhu et al. 2004) or Jordan, one of the ten most water stressed countries of the world (Abdulla & Al-Shareef 2009); in highly populated precincts of Beijing (Zuo et al. 2010); and developing precincts of Africa (Cowden et al. 2006).

Conventional rainwater tanks generally store stormwater runoff from roofs for non-potable uses which may include flushing toilets, washing clothes and irrigating gardens. In suburban locations with seasonal rainfall, area constraints often prohibit large storages which are necessary to avoid excessive overflow or frequent loss of supply. Thus, rainwater storage and reliability of supply have been significant factors in system design and performance assessment. However, if the rainwater demand is insufficient, tanks may operate inefficiently, overflow excessively and creating urban waste as stormwater runoff. To avoid this rainwater systems should be designed to supply all approved non-potable end uses, rather than reliably supplying just a few.

Fortunately, rainwater tanks offer more than just an alternate water supply for residential and commercial premises. One variation to the conventional tank is to install a trickle release outlet to slowly drain a pre-set volume of approximately the top 25% to 50%. This 'leaking tank' approach may facilitate moderating tank overflow (Coombes et al. 2003); augmenting municipal water supply via downstream independent harvesting (Brodie 2009); reducing catchment-scale water demand via downstream harvesting and irrigating community grounds (Townsend 2012); reducing the effects of the urban heat island (Coutts *et al.* 2007) via passive irrigation (Burns *et al.* 2012); potentially reduce flooding, though limits with tank sizes and adoption will restrict the effectiveness of this strategy; and, of principal interest to this research due to the environmental outcomes, assisting to restore aspects of pre-urban hydrology in urban streams by providing environmental flows and modulating surface runoff volume and frequency (Burns et al. 2010; Taylor 2012b, 2012a).

Restoration of pre-urban stream hydrology is an integral objective of recent advances in urban design and development including water sensitive urban design (WSUD) in Australia (Water by Design 2009), low impact development in the USA (EPA 2000), low impact urban design and development in New Zealand (van Roon 2011), sustainable drainage systems in the UK (Dickie et al. 2010) and eco-efficient water infrastructure in Asia-Pacific (UNESCAP 2009). Thus, it is apparent that rainwater tanks should be viewed as having two duties: (1) to provide an alternate water supply; and (2) to intercept roof runoff and provide environmental flows to assist with restoring pre-urban hydrology in urban streams. However, to date, there is no mention in the literature of how to define, estimate and analyse this dual-duty performance. Therefore, providing this knowledge is central to this dissertation.

These two duties are storage competitive but also somewhat complementary. Consuming rainwater and creating environmental flows will renew runoff interception capacity but environmental flows are expected to reduce rainwater supply reliability. Thus, it is essential to analyse storage arrangements and operating conditions for rainwater tanks which release environmental flows to ensure one duty is not excessively sacrificed for the benefit of the other. Defining and analysing these storage arrangements and operating conditions is also central to this dissertation.

Further rationale for dual-duty rainwater tanks can be found in recent studies of implementing WSUD. McAuley *et al.* (2012) examines opportunities to implement WSUD in Sydney catchments to improve stream health and prevent the 'urban-stream-syndrome' (Meyer et al. 2005; Walsh et al. 2005a). This research is based on a recent study in Melbourne (Walsh et al. 2005b) which have informed catchment management initiatives in Queensland (QDIP 2009). McAuley *et al.* (2012) concludes that stream flow restoration cannot be achieved within 50 years without robust private property WSUD retrofits. In the short-term, implementation of sufficient WSUD retrofits is generally prohibited by area constraints. This is due to local authorities owning insufficient suitable land for retrofits, together with low redevelopment rates, which limits the applicability of essential development conditions.

To supplement the initiative of local authorities and achieve timely results, incentives for implementing WSUD in private properties is essential, together with examining enhancements to the allotment-scale WSUD approach. Incorporating rainwater tanks in the allotment-scale framework for WSUD retrofits is highly relevant as water containment, consumption and creating environmental flows, are essential to reduce urban runoff and improve urban stream hydrology (Walsh et al. 2010). Also, as previously mentioned, rainwater tanks are commonplace and adoption is increasing. Thus, simple and inexpensive modifications to existing rainwater tanks, coupled with establishing the dual-duty design as standard practice, could potentially provide an avenue to expedite stream restoration in urban catchments.

Currently, conventional and leaking rainwater tanks are fixed in their operation. This may be problematic for combining the storage competing duties of water supply, runoff interception and environmental flows. Especially considering the variability of the broader systems associated with rainwater tanks, such as, the dependence of outdoor water use on daily maximum temperature and rainfall (Taylor 2012c) and the seasonal variability of rain event frequencies (Leonard et al. 2008). With conventional rainwater tanks, water use reduces during wet periods and runoff interception may be insufficient for restoring desirable stream hydrology. While with a leaking rainwater tank, the reliability of water supply may be reduced by providing excessive environmental flows during dry periods. It is apparent that an adaptive approach to managing rainwater storage through environmental flows may be necessary to maximise the benefits of dual-duty rainwater tanks.

It is envisaged water sensitive cities of the near future will develop adaptive and multifunctional infrastructure among other capacities (Water by Design 2009). Adaptation may include responding to change in climate and population, and in the context of this research, change in rainfall and water demands. As water use can be related to rainfall it seems prudent that rainfall statistics or forecasts would provide a basis for establishing adaptive management practices.

Forecasts and statistics of rainfall or stream flow are commonly used to operate large-scale reservoirs with duties comprising municipal water supply, hydroelectric generation, agriculture irrigation, flood control, or any combination of (Collischonn et al. 2007; Hejazi et al. 2008). To date, there appears to be no application of these principles to control rainwater tanks. This is not surprising considering the tasks of interpreting forecasts and statistics, measuring storage, monitoring water use and calculating releases, cannot be easily achieved with the status quo of low-technology rainwater tanks. However, this is the integration age and it is feasible to imagine a small control system capable of economically automating these tasks by following preset or dynamic operating rules.

Thus, conventional, leaking and adaptive rainwater storage arrangements (Fig. 1-1) should be investigated to find the optimum storage configuration and operation that achieves the maximum dual-duty performance for rainwater tanks.

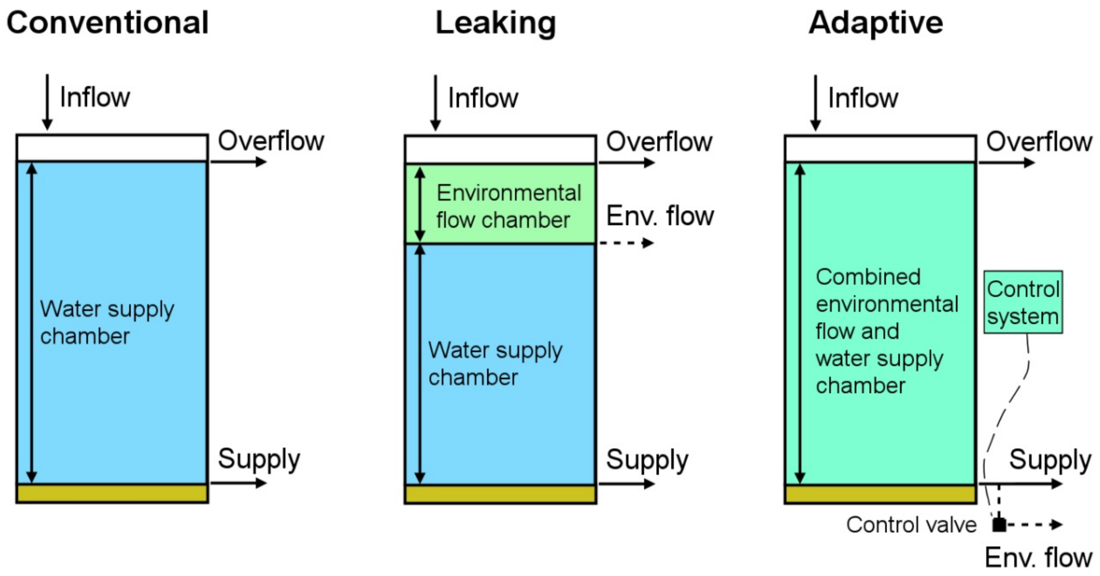


Fig. 1-1 Rainwater tank storage arrangements with alternatives for environmental flow. Note that with the leaking scenario, a physical partition between chambers is not necessary but this virtual separation is defined by the fixed position of the gravity-draining environmental flow outlet.

1.2 Hypothesis

This dissertation explores the hypothesis that environmental flow from rainwater tanks will increase their dual-duty performance; an adaptive approach for managing releases should provide superior results; and dual-duty performance of rainwater tanks could be rapidly determined from dimensionless relationships to rainfall statistics and design parameters, which represent the climatic zones and urban settings commonly found in Australia.

Some additional research questions include: (1) to what extent do environmental flows diminish rainwater supply; (2) are other allotment-scale WSUD components needed in conjunction with rainwater tanks to achieve restoration of stream hydrology; and (3) to what extent does the dual-duty performance vary over the spectrum of urban residential living typically found in Australia?

To test this hypothesis and answer these questions the following objectives are achieved: (1) to determine a method of assessing the stream restoration efficacy and dual-duty performance of rainwater tanks; (2) to establish what design parameters significantly influence the performance of rainwater tanks; (3) to develop methods of applying rainfall statistics and forecasts to achieve adaptive management of environmental flows; and (4) to correlate dual-duty performance with system design parameters and climate indices, to facilitate rapid performance assessment.

Original contributions to knowledge include: (1) an improved framework for dual-duty design and assessment of rainwater tanks which focuses on minimising the degradation and demand urban centres place on contiguous water resources, which shall expedite the development of water sensitive cities; (2) a simplified method to estimate outdoor residential water use, which shall advance water demand management assessment; (3) a method to extend the limited archives of rainfall forecasts, which shall facilitate long-term assessment of the daily operation of adaptive rainwater tanks and other forecast dependent systems; and (4) introduction of dimensionless fractions which correlate rainwater harvesting parameters and rainfall statistics to dual-duty performance of conventional and leaking rainwater tanks.

1.3 Structure of the dissertation

The dissertation is structured by progressive development of a comprehensive mass-balance behavioural simulator of dual-duty rainwater tanks, UrbanTank ©, followed by applications of UrbanTank to study the theoretical dual-duty expectations of rainwater tanks (Fig. 1-2).

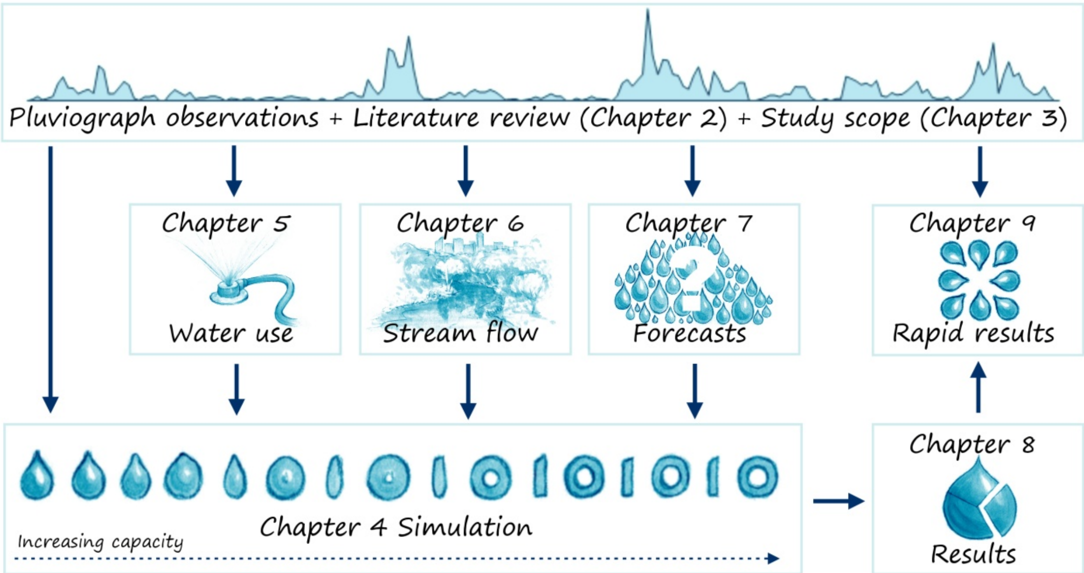


Fig. 1-2 Structure of the dissertation

The core components of UrbanTank are described in Chapter 4. Pluviograph observations are initially used as an input time-series for the simulation but also the data is correlated to outdoor residential water use in Chapter 5; applied to derive hypothetical pre-urban stream hydrology in Chapter 6; and applied to increase the duration of rainfall forecast archives in Chapter 7. The predictive capacity of the simulator is enhanced with each of these studies.

Finally, in Chapter 9, daily rainfall statistics and system parameters are correlated to the dual-duty performance estimates from UrbanTank to establish a rapid method of deriving the performance of conventional and leaking rainwater tanks.

The development of the thesis is also outlined by chapter summaries (Table 1-1).

Table 1-1 Thesis chapter outline

Chapter 2 Literature review

A review of literature pertaining to modelling the volumetric performance of rainwater tanks is presented in Chapter 2. Modelling aspects include methods to measure performance, methods to simulate rainwater tanks, current household water demand, studies of roof runoff hydrology and applications of first flush systems. Also the role and support of rainwater tanks in water sensitive urban design was reviewed. The key outcomes of the chapter include recommending new performance metrics and a new simulator for modelling dual-duty and adaptive rainwater tanks.

Chapter 3 Study context and scope

Following on from the results of the literature review in Chapter 2, a yield sensitivity analysis of conventional rainwater tanks was examined to refine the research scope. Areas of research essential to qualifying results and increasing the research relevance include a model to predict outdoor water use, which is discussed in Chapter 5; new adaptive approaches for managing environmental flows, which is discussed in Chapter 4; a method to supplement daily archives of rainfall forecasts, which is discussed in Chapter 7; and a rapid method for estimating dual-duty performance, which is discussed in Chapter 9.

Chapter 4 Modelling adaptive rainwater systems

From the literature review in Chapter 2 it was discovered the current modelling applications were not suitable for simulating dual-duty and adaptive rainwater tanks. Therefore, Chapter 4 describes the development of a mass-balance behavioural model to simulate all varieties of rainwater tanks included in the study scope. The four principal components of the model are catchment, storage, demand and operating rules. Where possible, model parameters are calibrated by independent empirical studies. The chapter concludes by introducing new performance metrics and validating simulated results against current simulation practices and independent field measurements.

Chapter 5 Outdoor water use

The yield sensitivity analysis in Chapter 3 revealed the performance of rainwater tanks is sensitive to the daily variation in water use. Therefore, Chapter 5 presents a model that correlates this variability to climatic indices of daily maximum temperature and daily rainfall. The model estimates monthly portions of annual outdoor water use which are verified in locations that represent climatic zones and urban centres throughout Australia. The diverse climates represented provide a wide relevance for the model. The results of Chapter 5 build on from the core simulation components discussed in Chapter 4.

Associated publication:

Taylor, B.A. 2012c, 'Predicting normalised monthly patterns of domestic external water demand using rainfall and temperature data', *Water Science & Technology: Water supply*, vol. 12, no. 2, pp. 168-178.

Chapter 6 Dual-duty assessment of rainwater tanks

From the literature review in Chapter 2 it was recommended that new performance metrics should be established to assess the dual-duty performance of rainwater tanks. In Chapter 4 the volumetric utility metric was introduced to achieve this, based on refinements to the environmental benefit index. Chapter 6 details these refinements and applies the volumetric utility metric in a dual-duty sensitivity analysis of leaking rainwater tanks. The analysis confirms the research hypothesis that dual-duty performance is improved by enabling environmental flows from rainwater tanks.

Associated publication:

Taylor, B.A. 2012, 'Emulating pre-urban initial rainfall losses and restoring baseflow with rainwater harvesting, paper presented to the *7th International Conference on Water Sensitive Urban Design*, Melbourne, Australia, 21-23 February 2012.

Chapter 7 Supplementing daily archives of rainfall forecasts

In refining the research scope in Chapter 3 it was identified that rainfall forecasts could be used for adaptive management of environmental flows. However, the short duration of archives of rainfall forecasts would limit the simulation period and prohibit long-term assessment. Therefore, Chapter 7 examines four methods to supplement forecast archives by combining historic daily rainfall observations with error behaviour of current rainfall forecast techniques. A Behavioural-Monte Carlo method is recommended that supplements archives based on the skill of gridded rainfall forecasts in all Australian capital cities. The results of Chapter 7 are incorporated into the simulation of rainwater tanks where environmental flows are controlled by the severity of rainfall forecasts.

Associated publication:

Taylor, B.A. 2012, 'Enhancing rainwater harvesting with short-term rainfall forecasts in water sensitive cities', paper presented to the *OZWater12 conference - Sharing knowledge, planning the future*, Sydney, Australia, 8-10 May 2012.

Chapter 8 Rainwater system performance examined

The dual-duty performance of adaptive rainwater tanks is introduced in Chapter 8 and compared to that of conventional and leaking tanks. The results demonstrate conventional rainwater tanks are consistently inferior to leaking and adaptive alternatives. Also, the adaptive approach is not consistently better than the simpler leaking tank arrangement. Thus, the adaptive approaches were precluded further analysis. The chapter concludes with an extended analysis where general relationships are discussed between dual-duty performance and rainwater harvesting system parameters of roof area, rainwater demand, tanks volume and urban density.

Chapter 9 Rapid performance estimation

The sensitivity analysis in Chapter 3 identified that a rapid method for estimating dual-duty performance and optimum design is essential to increase the relevance of research results. Thus, methods based on rainfall statistics and rainwater harvesting design parameters are introduced in Chapter 9. The assessment is refined to conventional and leaking rainwater tanks. The dimensionless regressions are based on the simulated results from the base scenario and extended analyses in Chapter 8.

Associated publication:

Taylor, B.A. 2011, 'Rapid estimation of rainwater yield throughout Australia and review of Queensland rainwater harvesting operating policy', paper presented to the *Escaping silos SSEE 2011 international conference*, Brisbane, Australia, 24-26 October 2011

Chapter 10 Conclusions and recommendations

The principal outcomes of the dissertation are summarised to demonstrate the hypothesis has been thoroughly tested and the results provide a valuable contribution to promoting dual-duty rainwater tanks and their humanitarian and ecological benefits. Limitations with the research methodology and scope are summarised and recommendations are made for future research.

Chapter 2 Literature Review

A review of literature pertaining to modelling the performance of rainwater systems is presented. Modelling aspects includes methods to measure performance, methods to model rainwater systems, current household water use, studies of roof runoff hydrology, applications of first flush systems and the role of rainwater tanks in water sensitive urban design.

2.1 Introduction

The process of reducing the post-developed volumetric stormwater discharge to the pre-developed condition has been termed a water balance approach to stormwater treatment (Coombes *et al.* 2003; Bradford *et al.* 2008). The potential to achieve this approach with rainwater tanks is acknowledged in many guidelines for WSUD, as well as the design and installation standard for rainwater tanks (SA 2008).

This literature review provides an overview of recent economic studies of rainwater tanks before examining the role of rainwater tanks in WSUD projects throughout Australia. Also, reviewed are the metrics adopted for assessing rainwater tanks, common simulation practices, household water use, roof runoff hydrology and first flush diverters.

2.2 Economics of rainwater tanks

Research into the economics of rainwater harvesting is extensive (Coombes 2006a; Mitchell & Rahman 2006; Vale & Ghosh 2006; Sturm *et al.* 2009; Tam *et al.* 2010). Often the whole-of-life cost or levelised cost methods are used to compare rainwater yield to other water sources (MJA 2007a, 2007b; Roebuck 2007). Positive results have been reported using cost benefit analysis for rainwater harvesting systems in Beijing (Zuo *et al.* 2010). This type of analysis allows consideration of the benefits to all stakeholders and the cost of inaction. Zuo *et al.* (2010) demonstrates two-thirds of 267 rainwater harvesting systems returned at least a unit benefit to cost ratio and some returned twice the benefit over cost. Rainwater harvesting is proven a viable water supply option even in the most densely populated cities.

Triple bottom line analysis is now essential for water management (Braga 2003; Schneider *et al.* 2003). It has been demonstrated that rainwater systems are ahead of centralised water supply options when considering the triple bottom line (White 2009). White uses this approach to demonstrate Queensland rainwater rebates should be refined and maintained indefinitely as they are the most cost effective means of providing urban and rural water security.

The Urban Water Security Research Alliance is currently investigating SEQ water strategy with focus on triple bottom line analysis of stormwater harvesting, which is expected to include rainwater systems (UWSRA 2009). The triple bottom line analysis is increasingly being used to measure sustainability in the water sector and consistently demonstrates the value of rainwater systems (Syme *et al.* 2004; Lucas *et al.* 2006; Capati & Hollingsworth 2007; Troy & Spearritt 2008).

The economic benefits of rainwater tanks have been demonstrated by these studies however the environmental benefits of restoring aspects of pre-urban stream hydrology are seldom considered and are critical for a holistic view. Further investigation is recommended to encompass the dual-duty performance of rainwater tanks economic assessment this is beyond the scope of this research.

2.3 WSUD and rainwater tanks

The impacts of urbanisation on the environment are widespread and clearly extend beyond changes to stream hydrology. Over the last decade, interest in WSUD and water sensitive cities (Water by Design 2009) has increased and created extensive resources for modelling, designing and installing WSUD elements (Table 2-1). Typically WSUD performance is assessed with the Model for Urban Stormwater Improvement Conceptualisation (MUSIC) (eWater 2011). Guidelines for development and modelling of WSUD unanimously endorse the use of rainwater tanks as a means to mitigate stormwater runoff volumes, and to a lesser extent, as a treatment measure for stormwater quality. The benefits of dual-duty rainwater tanks are highly relevant to the objectives of the WSUD body of knowledge.

Table 2-1 Australian metropolitan WSUD and MUSIC guidelines

Capital city	WSUD Guidelines	MUSIC Guidelines	Supports rainwater tanks
Adelaide	(SADHPL 2010)	(SADHPL 2010)	Yes
Brisbane	(Water by Design 2006)	(Water by Design 2010)	Yes
Canberra	(ACTPLA 2009)	(ACTPLA 2009)	Yes
Darwin	(NTDPI 2009a)	(NTDPI 2009b)	Yes
Hobart	(TDPIWE 2006)	-	Yes
Melbourne	(Melbourne Water 2010a)	(Melbourne Water 2010b)	Yes
Perth	(PDC 2006)	-	Yes
Sydney	(UPRCT 2004; CMA 2010; City of Sydney 2012)	(BMT WBM 2010)	Yes

2.4 Measuring rainwater tank performance

Since growing in popularity, many performance metrics have been applied to rainwater tanks to communicate their benefits. Metrics examined include rainwater yield, supply reliability, augmented supply, overflow, environmental benefit, hydrologic effectiveness, storm storage, probable initial airspace storage and effective imperviousness.

2.4.1 Rainwater yield

The performance of rainwater tanks is most commonly measured using long-term average annual yield (Mitchell 2007), also known as mains water savings (Coombes 2006a) or rainwater yield (Argue & Pezzaniti 2006; Coombes & Barry 2007; MJA 2007a; Hanson *et al.* 2009). Rainwater yield is the volume of water supplied by the rainwater tank over a given time. Rainwater yield varies annually, seasonally and daily. It is typical to average yield over several years. Calculating the rainwater yield is the principal aim of rainwater tank simulators, however, this value alone can have little meaning.

Consider hypothetical cases A and B where average annual rainwater yield is 60 kL and 45 kL, respectively. This informs water supply authorities of demand reduction potential, but without consideration of the rainwater demand, no insight is given to which system is the more efficient or where further improvements can be made.

Recently abolished minimum water saving requirements were based on rainwater yield targets and established for domestic (QDIP 2007a) and commercial buildings (QDIP 2007b) in Queensland. Domestic water saving targets were grouped by local government area with average annual household water savings ranging from 16 kL to 70 kL. A review of achieving the 70 kL target has shown that annual average water savings in most cases would be only half the target (Beal *et al.* 2009).

Average annual rainwater yield will be included as a performance metric in this study due the broad relevance and being a component of the tank water balance. Yield will also be applied to demonstrate the sensitivity of model estimates to parameter values in the parameter sensitivity analysis, and to verify model results against other simulators and field measurement.

2.4.2 Supply reliability

Supply reliability offers greater comprehension than rainwater yield by revealing performance as a portion of demand. The reliability of rainwater supply can be measured in two ways: time-based reliability and volumetric reliability. Time-based reliability is the percentage of days each year when rainwater yield is able to meet demand (DA 2004; Kim & Yoo 2009). Barry and Coombes (2008) report the reverse and use a finer time-step in the average annual maximum failure hours per day.

Long-term volumetric reliability (Mitchell 2007; Zhang *et al.* 2009) is the ratio of rainwater yield to rainwater demand (Hanson *et al.* 2009; Khastagir & Jayasuriya 2010) and can also be referred to as, water saving efficiency (Jenkins 2007; Khastagir 2008) and potential water savings (Abdulla & Al-Shareef 2009). Like time-based reliability, results are usually averaged annually over the simulation period.

Returning to the hypothetical cases A and B where rainwater yield was 60 kL and 45 kL, respectively, and adopting household rainwater demands of 100 kL and 50 kL, respectively, gives supply reliabilities of 60% and 90%, respectively. Thus, the latter case is more reliable while providing less rainwater. The latter case is limited by rainwater demand and could potentially provide greater yield if rainwater demand was increased. However, by increasing demand the reliability of the system is likely to reduce. Therefore, supply reliability is not a good indication of the true potential of a rainwater system.

Supply reliability is broadly used within the engineering literature. The results are informative and relevant to stakeholders in local authorities, developers and homeowners. Time-based reliability, using a daily time step, is expected to marginally exceed volumetric supply reliability where days of partial supply are undistinguished from full supply. However, supply reliability has limits and an alternative is recommended which promotes the consumption of rainwater rather than reliably supplying a small number of end uses.

2.4.3 Augmented supply

Mains top-up supply is the volume of water needed to augment rainwater yield to meet demand (Barry & Coombes 2008). In reservoir analysis, this is similar to hydrologic uncertainty (Hejazi et al. 2008). Barry and Coombes analyse the sensitivity of long-term yield and time-based supply reliability to varying top-up volumes and rates. Most local water authorities now prefer switching between mains and tank supply, rather than the trickle top-up arrangement. This removes the operational volume needed for top-up supply and float valve actuation from the tank, thus maximising rainwater and storm storage capacity and simplifying tank components.

In the context of this research, water supplied from sources other than rainwater harvesting, including mains top-up supply will be more generally termed imported water and will be included as a performance metric in this study to provide a measure of household dependence on reticulated water supplies.

2.4.4 Overflow

Overflow occurs when any part of the rainwater system is overwhelmed (Coombes & Barry 2008a). Sources of overflow include gutter overflow and tank overflow. Monitoring of overflow is important to ensure a balance between minimum ecological flows (Ngigi 2003; Bradford *et al.* 2008) and impacts from excessive flows (Wang *et al.* 2008). (Guo & Baetz 2007) provide extensive numerical analysis to estimate total annual overflow volume for green building applications. This study explains overflow volume as the product of the annual number of cycles and the expected overflow value per cycle.

One study reviewed the effects of rainwater systems on combined sewer inflow by focusing on overflow analysis (Vaes & Berlamont 2001). This study investigated the changes to the intensity frequency duration of urban runoff with and without rainwater tanks. The study concludes by providing modified design storms for urban catchments where rainwater tanks are installed, which demonstrates their capacity to mitigate urban stormwater runoff.

In the proposed research overflow will be examined as a component of the tank water balance and used as part of more comprehensive methods to determine the environmental benefit of mitigating excess runoff.

2.4.5 Environmental benefit index

The environmental benefit of allotment scale WSUD projects such as that proposed for Little Stringybark Creek, Melbourne, can be calculated online (Walsh *et al.* 2012). The environmental benefit index (EBI) is founded on a new generation of stormwater management objectives aimed at protecting stream health (Walsh *et al.* 2010). The index is based on relationships between rainfall and evapotranspiration loss curves for catchments throughout the globe (Zhang *et al.* 2001; Komatsu *et al.* 2011) and is also consistent with rainfall to surface runoff curves for catchments throughout Australia (Boughton & Chiew 2007).

The index is derived from the mean of four sub-indices, each based on maintaining aspects of stream hydrology which stream ecosystems are particularly vulnerable to (Poff *et al.* 2010). Essential aspects include frequency of surface runoff, volume of sub-surface flow, water quality and total volume of flow. The index can be applied to catchments beyond Melbourne by the generalised relationships of average annual rainfall to index parameters provided by the developers.

Therefore, the EBI will be adopted herein as the principal method to assess the environmental benefits of various storage arrangements and operating methods for rainwater tanks.

2.4.6 Hydrologic effectiveness

The use of hydrologic effectiveness in rainwater tanks was recently introduced (Jenkins 2007) by applying the study of stormwater treatment capacity of wetland systems (Wong & Somes 1995). Jenkins (2007) defines hydrologic effectiveness as the ratio of average annual rainwater yield to average annual runoff. However, the hydrology of the broader rainwater systems includes evaporation from roof surfaces and dead storages in gutters, which is disregarded by adopting roof runoff over total rainfall. The EBI offers a more comprehensive approach of measuring the catchment management performance of rainwater tanks. Thus, the hydrologic effectiveness metric will not be investigated further.

2.4.7 Storm storage

To mitigate excessive runoff from urban areas, Queensland stormwater management guidelines recommend intercepting a runoff depth of 10 to 15 mm/day over all impervious surfaces (Eadie 2009). This approach is consistent with earlier studies of undeveloped forested catchment in Melbourne where stormwater runoff generally occur when rainfall exceeded 15 mm/d (Walsh *et al.* 2005b).

In an independent study, Coombes *et al.*(2000) monitored a stormwater system in Newcastle which included underground rainwater tanks and found that almost total containment of stormwater was achievable for this suburban community. It follows that rainwater tanks are capable of storm storage and potentially achieving daily runoff interception that is sufficient to return the water balance of pre-urban surface runoff.

To achieve compliance with the Queensland guidelines, the storm storage interception capacity needs to be renewed within 24 hours without discharge from the catchment (Eadie 2009). This fixed daily interception depth is not consistent with the daily infiltrative and evaporative losses of pre-urban catchments throughout Queensland (Tularam & Ilahee 2007) and South-East Australia (Hill *et al.* 1997; Burns *et al.* 2010). These studies demonstrate daily losses follow a distribution which could potentially range from 2 to 200 mm for a single rain event and these losses are mostly dependent on the antecedent moisture of the catchment.

The EBI offers a more comprehensive method to determine the efficacy of rainwater systems to restore pre-urban surface runoff. Consequently, storm storage will not be considered further.

2.4.8 Probable initial airspace storage

Storm storage is also known as probable initial airspace storage available (PIASA) (Coombes *et al.* 2003). In their study, the performance of combined residential stormwater and rainwater tanks in Sydney is reported using average recurrence intervals (ARI). The study shows PIASA increases with greater ARI. This desirable result is due to the uniform rainfall distribution observed in Sydney where the high frequency of small rain events coincides with low winter outdoor water use and limited storm storage. Moreover, large storm events occur in summer when outdoor water use and storm storage is high.

More recently, PIASA studies in rainwater tanks have focused on other locations including Adelaide, Brisbane and Melbourne to establish the performance in regions with winter and summer dominant rainfall (Coombes & Barry 2008a). Results from Brisbane show, PIASA reduces with high ARI and summer dominance of rainfall. This undesirable result is due to the higher frequency of large rain events that occur in regions with summer dominant rainfall. In these locations, it may be challenging to consolidate the dual-duties of water supply and storm storage with rainwater tanks, due to limitations with storage and operating flexibility.

However, as previously recommended, the capacity of rainwater tanks to restore aspects of pre-urban hydrology will be measured by the EBI. Therefore, measurements of PIASA will not be considered in the proposed research.

2.4.9 Effective imperviousness

Ladson *et al.* (2006) reports detrimental stream health is related to the direct connection of impervious catchments to streams. Impacts from urbanisation are related to stream flow, geomorphology, water quality and stream ecology in a process referred ‘the urban stream syndrome’ (Meyer *et al.* 2005; Walsh *et al.* 2005a). Ladson *et al.* (2006) introduces a normalised drainage connection index where zero corresponds to disconnecting enough impervious catchment to mimic the pre-developed hydrology. In the case reported, disconnection is achieved by treating the first 15 mm of daily rainfall. Moreover, an index of one corresponds to retaining

1 mm of daily rainfall, as generally observed from directly connected impervious catchments. Various allotment scale and streetscape treatment options are investigated. Allotment scale WSUD elements are limited to permeable pavers, 6 kL rainwater tanks and rain gardens.

The idea of disconnecting impervious catchments with the use of rainwater tanks for a variety of infill developments has recently been extended beyond domestic applications to include commercial premises (Coombes 2009). In this study, compliance of development conditions is demonstrated by analysis of weighted runoff coefficients and establishing a simple retention number. The purpose of the retention number appears to be to expedite the analysis by avoiding calculations of ARI 5 year peak discharges. However, this approach has not been adopted as standard practice and will be precluded from further investigations.

Effective imperviousness and treating a daily runoff depth are essentially the same approach. An effective imperviousness of zero is equivalent to treating a runoff depth of 10 mm/day, where the fraction of imperviousness of the catchment is not greater than 40%. Moreover, an effective imperviousness that equals total impervious is equivalent to treating a runoff capture depth of 1 mm/day. However, the EBI presents a more robust method to measure the environmental benefit of rainwater tanks and WSUD projects and will therefore be used over the effective impervious method.

2.4.10 Statistical representation

Average annual statistical representations are common in rainwater harvesting studies. In Australia, a positive skewness is typical for long-term hydrological data (IEAust 2001). Skewness is a measure of asymmetry distribution about the mean and usually implies the peak distribution departs from the mean. The greater the skew, the mean becomes less relevant as a measure of central tendency. It is generally perceived, by the public, that there is equal chance that the mean value will or will not be exceeded. In the case of positive skewness, there is greater chance the mean value will not be exceeded. This implies the use of average annual values may over predict performance and mislead those not familiar with such statistics. Therefore, distributions of annual results will be presented with boxplots to demonstrate the temporal variability of performance estimates.

Furthermore, limited statistical methods were discovered that adequately determine the performance of rainwater tanks over a range of system design parameters that are commonly found in urban residential settings in Australia. Therefore, to increase the relevance of research results a rapid method for determining rainwater tank performance will be developed.

2.4.11 Summary of adopted performance metrics

In summary, various metrics will be included in the proposed research (Table 2-2). New metrics are recommended to provide a more comprehensive assessment of water supply and dual-duty performance, and these are introduced in Chapter 4. To complete the water balance, environmental flow will be included. Also, refinements are needed to the EBI for application to rainwater tanks within the scope of this research, and this is discussed in Chapter 6.

Table 2-2 Performance metrics adopted for rainwater tanks

Metric	Units	Application
Average annual rainwater yield Y	kL	Applied in a parameter sensitivity analysis to refine research scope in Chapter 3. Applied to verify model estimates from conventional rainwater tanks in Chapter 4 and part of the water balance of all rainwater tanks studied in Chapter 8.
Average annual rainwater system overflow O	kL	Used within the EBI to demonstrate efficacy of restoring pre-urban flow-frequency as discussed in Chapter 6 and part of the water balance of rainwater thanks studied in Chapter 8.
Average annual environmental flow EF	kL	Component of water balance for leaking and adaptive rainwater tanks.
Average annual imported water IW	kL	Adopted to demonstrate the household reliance on municipal water supply and will be included in Chapter 8.
Average annual environmental benefit index EBI	(-)	A simplified method is adopted as the principal measure of restoring aspects of pre-urban stream hydrology, which is developed in Chapter 6.

2.5 Modelling rainwater tanks

The literature contains many methods for estimating the performance of rainwater tanks and in order of increasing complexity some examples include simplified formula (Abdulla & Al-Shareef 2009; ACT Gov. 2010), feasibility simulation (enhealth 2004; egrants 2010) and many deterministic simulation models. The accuracy of estimates typically increases with the complexity of the method but similarly the demands on the modeller may also increase, such as, the preparation and validation of input data and knowledge of model parameters. Simplified formula and feasibility simulation are limited in accuracy and their functionality which precludes use for the proposed research. Therefore, the review will be limited to deterministic simulation models.

2.5.1 Deterministic simulation of rainwater systems

Deterministic simulation is the process of constructing a mathematical model of a system to derive single output from a combination of input parameters which related to a particular scenario of interest. In this case the system is all the components of a rainwater harvesting solution; the output is most commonly rainwater yield or another metric for assessment of the dual-duty performance; and model input may include rainfall data, roof area, tank volume, rainwater use pattern and storage arrangement.

Where continuous time-series are used as inputs for the model, such as rainfall observations, then the process is known as continuous simulation (Ward *et al.* 2010). Model input parameters are usually based on field research and model estimates should be validated by independent simulation or field measurements. Guidance on deterministic simulation for water cycle modelling is extensive (Mitchell *et al.* 2001; Lucas *et al.* 2006; Mitchell & Diaper 2006; Coombes & Barry 2007; Mitchell 2007) and as such many models have been developed.

Mitchell *et al.* (2007) provides a comprehensive list of 65 integrated urban water management models. All models were reviewed for their capacity to simulate rainwater tanks, which refined the list to Aquacycle (Mitchell *et al.* 2001), BASIX (BASIX 2010), House Water Expert (CSIRO 2007), Hydro Planner (Grant 2006), MIKE URBAN and software suite (DHI 2010), MUSIC (eWater 2010), PURRS (Coombes 2002), Rainwater TANK (DEUS 2006; Vieritz 2007; egrants 2010), XP-

SWMM (XP-Software 2010), UrbanCycle (Hardy *et al.* 2005), UVQ (Mitchell & Diaper 2005) and WaterCress (WaterCress 2010). A similar study by Ward et al. (2010) revealed further potential models comprising DRHM (Dixon A. *et al.* 1999), Rewaput (Vaes & Berlamont 2001), RWIN(KOSIM) (Herrmann & Schmida 1999), RCSM (Fewkes 2004), RSD (Kim & Han 2006) and RainCycle (Roebuck & Ashley 2006). Finally, RAINTANK (enter 2010) and the Environmental Benefit index (EBI) calculator (Walsh *et al.* 2012) was also discovered from the literature.

For many models, rainwater harvesting was a supplementary component to detailed modelling of water supply or stormwater management schemes. Thus, a great variation was experienced in the functionality of the models and the resulting estimates. A critical review of the models was conducted with performance criteria comprising flexible continuous simulation period; daily or finer time-step; detailed output metrics; dual-duty performance; and ability to implement operating rules for environmental flows. It was discovered that all but PURRS had the desired functionality and even PURRS would require some modification to incorporate dual-duty operating rules (Table 2-3).

Table 2-3 Functionality of rainwater harvesting simulators

Simulator	Continuous simulation	Daily or finer time step	Detailed metrics	Dual purpose
Aquacycle	✓ flexible	✓ daily	✓	×
Basix	✓ fixed	✓ hourly	×	×
DRHM	✓ flexible	Being reviewed	×	×
EBI	✓ fixed	✓ 6 min	✓	✓
House water expert	✓ fixed	Not specified	×	×
Hydroplanner	Not suitable for allotment scale			
MIKE Urban	Not suitable for allotment scale			
MUSIC	✓ flexible	✓ flexible	×	✓
PURRS	✓ flexible	✓ 6 min	✓	✓
RAINTANK	✓ flexible	✓ daily	✓	×
RainCycle	✓ flexible	✓ daily	✓	×
Rainwater TANK	✓ fixed	✓ daily	✓	×
RCSM	✓ flexible	✓ flexible	✓	×
Rewaput	Software could not be sourced			
RSR	Software could not be sourced			
RWIN	✓ flexible	✓ 5 min	×	×
XP-SWMM	✓ flexible	✓ 6 min	×	✓
UrbanCycle	✓ flexible	✓ sub daily	Under development	
UVQ	✓ flexible	✓ daily	✓	×
WaterCress	✓ flexible	✓ daily	×	×

Unfortunately, permission was not given by the developer to modify PURRS so it was necessary to create a purpose built simulator for the proposed research. Creating this simulator was a major component of the dissertation.

2.6 Household water use

2.6.1 Household water use modelling

Herrera *et al.* (2010) and Qi & Chang (2011) provide a thorough review of applied and potential predictive models for forecasting domestic water use. Other demand prediction models have followed chaos theory (Chang *et al.* 2008), a radial basis function (Zhang *et al.* 2006), an ant algorithm (Li & Wang 2005), state space regression (Billings 1998), system dynamics modelling (Qi & Chang 2011), census tracks (Polebitski & Palmer 2010), deterministic smoothing algorithms (Aly & Wanakule 2004), multivariate econometric analysis (Qld DNR 2000; Babel et al. 2007), genetic programming (Nasseri et al. 2011) and non-parametric aggregation (Coombes 2002). Common to all models is a high dependence on local data in demand, climatic and/or demographic forms for regression and/or model training processes. Applying these methods broadly would be impractical, due to excessive processing and data limitations. Therefore, in order to conduct a broad assessment in all capital cities of Australia, an alternative is needed which greatly reduces data dependence and processing requirements. The details of this water use model are discussed in Chapter 5.

2.6.2 Household water use trends

In recent years, household water consumption throughout South-East Queensland was governed by the severity of water restrictions which have been replaced by permanent water conservation measures since late 2009 (Fig. 2-1). Given the widespread implication of the Millennium Drought, this pattern of water consumption is typical of many cities throughout Australia.

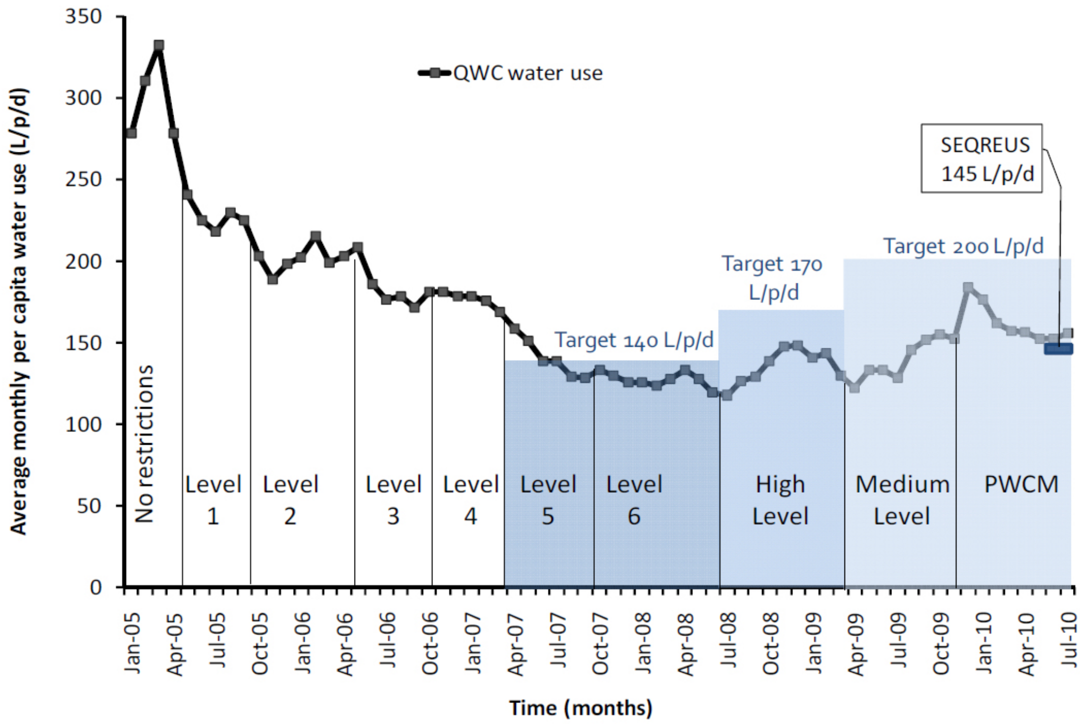


Fig. 2-1 SEQ per capita water use and water restriction levels from 2005 to 2010. Source: (UWSRA 2010)

In most Australian states and territories peak annual household water use from reticulated supply occurred at the start of the Millennium Drought in 2001, and for the average sized household ranged from 248 to 493 kL (Fig. 2-2). Some exceptions include an earlier peak (1997) in the Northern Territory and later peak (2005) in Tasmania. Most locations show similar response to the drought with consumption spiking initially and then returning to a level at or below the pre-drought short-term mean derived from the period 1994 to 1997. Exceptions were Western Australia where post-drought consumption declined but not to pre-drought levels and Tasmania, where consumption remains at peak levels. Currently (2012), annual average household consumption in most states and territories is similar to the national average of 216 kL, with 198 kL in ACT, 200 kL in NSW, 208 kL in Queensland, 198 kL in SA and 152 kL in Victoria (Fig. 2-2).

Recent estimates of average household water use in capital cities, taken from water utility production reports, are mostly consistent with estimates in corresponding states or territories (Fig. 2-2 and Table 2-4). One exception is lower water use reports in Brisbane and Perth. This anomaly is not surprising in Queensland given the population of Brisbane is 45% of the state (BoS 2012) and much of the population outside of South East Queensland experiences higher rainfall seasonality, which is shown in Chapter 5 to increase household water use.

However, the estimates for Perth poorly correlate with the state average despite the city having the highest state population percentage (74%), besides the ACT (BoS 2012). Also, Perth water use remains constant were all others cities have displayed a consistent response to the drought. Thus, some scepticism surrounds the water use estimates in Perth by the National Water Commission (NWC 2011).

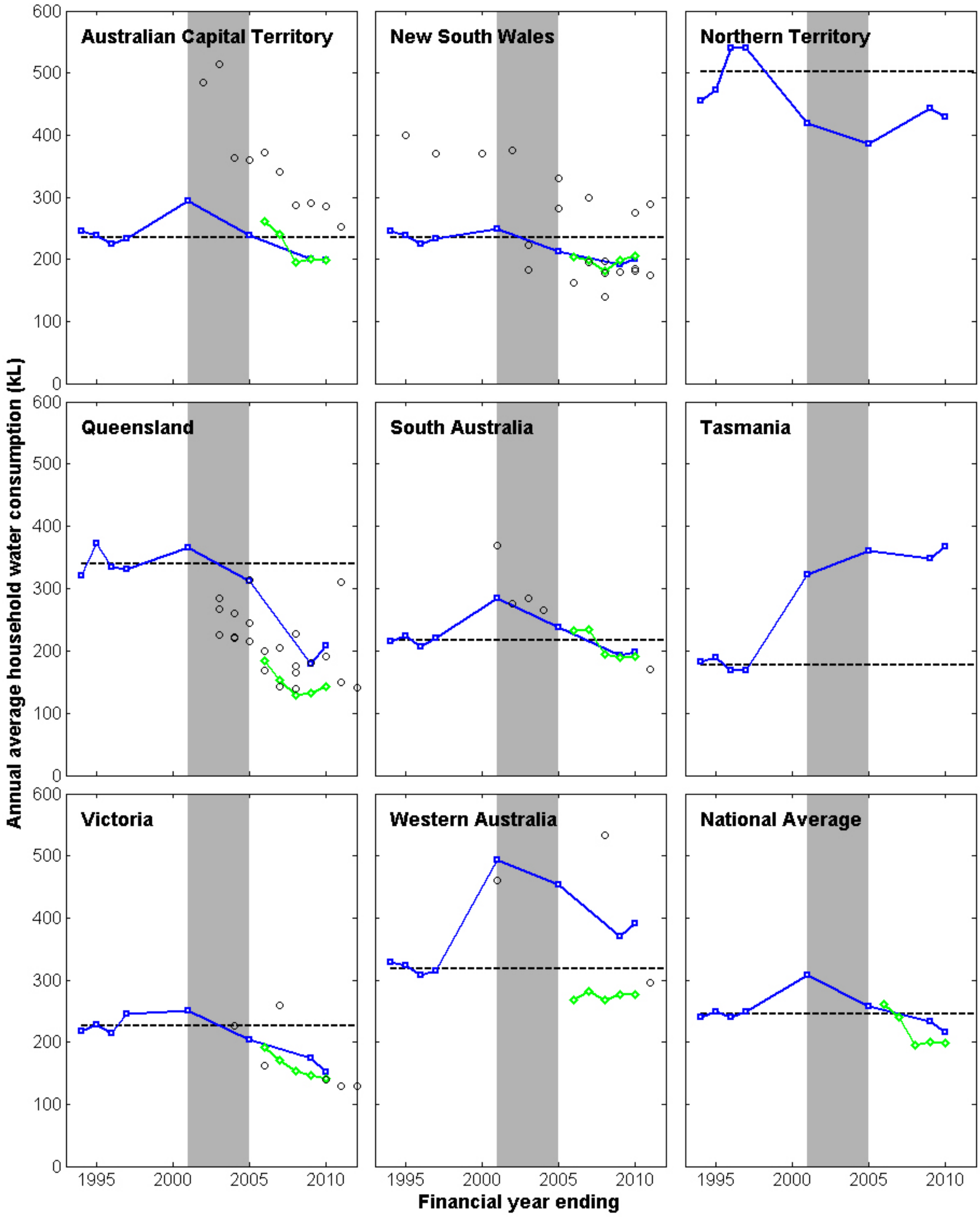


Fig. 2-2 Annual average household water use pre, during and post Millennium Drought; state and territory estimates (**blue**) adapted from (BoS 2000, 2003, 2005, 2006, 2007, 2009, 2010c, 2010a, 2011a, 2011b); capital city estimates (**green**) adapted from (NWC 2011; Cook *et al.* 2012); other estimates (**circles**) adapted from Table 2-4; and duration of Millennium Drought (**grey**) defined by DSEWPC (2006). Note that some estimates do not include water use from alternate supplies such as private bores, greywater recycling and rainwater tanks and drought period may have varied throughout Australia.

Table 2-4 Annual household water consumption estimates (2000 to 2012)

Source	**Key results**	**Study region**
New South Wales		
(Coombes *et al.* 2004)	183 kL from a single house	Carrington
(Coombes 2006a)	193 to 696 kL for various local government areas.	State wide
(Thyer *et al.* 2008)	222 down to 163 kL from 2003 to 2006	Newcastle
(SW 2009)	400 down to 275 kL from 1995 to 2011	Sydney
(Lucas & Coombes 2009b)	139 kL for household with three occupants	Hornsby
(Eroksuz & Rahman 2010)	Per capita demand rates per water use type	East coast
(Orr *et al.* 2011)	181 kL	Newcastle
(SW 2011)	277 kL	Sydney
(HWC 2011)	195 down to 175 kL from 2007 to 2011	Hunter Valley
(Ferguson 2011, 2012)	197 kL	Sydney
Queensland		
(QDNR 2000)	329 to 675 kL pre-Millennium Drought	State wide.
(Phillips *et al.* 2004)	285 kL	Caloundra
(Stewart *et al.* 2005)	286 to 416 kL	South East Qld.
(AWA 2005)	260 to 347 kL	South East Qld.
(Mead 2008)	223 down to 139 kL from 2004 to 2008	Toowoomba
(Gardner *et al.* 2008)	314 kL during winter-spring	Brisbane
(Lucas & Coombes 2009a)	228 kL/y for household with five occupants	Brisbane
(UWSRA 2010)	132 kL based on winter metering	South-East Qld.
(Beal *et al.* 2010)	154 to 201 kL for various local government areas.	South-East Qld.
(Turner *et al.* 2010)	240 down to 170 kL from 2003 to 2008	Hervey Bay
(Willis *et al.* 2011a; Willis *et al.* 2011b)	180 kL derived from average bulk supply of 191 L/p/d. Seasonal, diurnal and component patterns also reported.	Gold Coast

(McLaughlin 2011)	310 kL	Bundaberg
(UWSRA 2011b)	117 kL	South-East Qld.
(QWC 2011)	149 kL	South-East Qld.
(QGQWC 2012)	141 kL during winter	South-East Qld.
South Australia		
(SA 2004)	284 kL	Adelaide
(Fearnley *et al.* 2004)	370 kL	Adelaide
(Barton & Argue 2005)	276 kL	Adelaide
(Hurlimann & McKay 2006)	265 kL	Adelaide
(SAWC 2011)	171 kL	Adelaide
Victoria		
(Roberts 2005)	218 kL Component splits also reported	Melbourne
(Khastagir 2008)	162 kL and component distribution	Melbourne
(Troy & Spearritt 2008)	260 kL	Melbourne
(MW 2011)	130 kL	Melbourne
(MW 2012)	130 kL during winter	Melbourne
Western Australia		
(Loh & Coghlan 2003)	460 kL Seasonal, diurnal and component patterns also reported.	Perth
(Wasimi & Hassa 2011)	404 to 587 kL depending on household size and income.	Perth
(WC 2011)	296 kL	Perth
National or ACT		
(enhealth 2004)	110 to 270 kL (indoor only)	National
(ACTEW 2011)	260 kL	Canberra

In the Australian Capital Territory, almost the entire population reside in Canberra and the difference between the state and capital city estimates of average annual household water demand D_t is attributed to reporting frequency (Fig. 2-2). However, the water utility for the ACT, ACTEW, is not in agreement with these estimates. In their Annual Report (ACTEW 2011) D_t is consistently higher than NWC estimates and the Australian Bureau of Statistics (BoS). Fortunately, the discrepancy has reduced in recent years and these three institutions appear to be converging on a D_t of 200 kL.

Ferguson (2011, 2012) monitored D_t for a 12 month period ending June 2010 from 52 Sydney households fitted with rainwater tanks and concludes with an average D_t of 197 kL, which is consistent with the state average and the NWC report (Fig. 2-2); estimates from 255 households in Newcastle (Orr *et al.* 2011); the lower bracket of independent research throughout NSW (Coombes 2006a; Lucas & Coombes 2009b); earlier estimates of an inner-city house in Carrington (Coombes *et al.* 2004); and estimates in the latest Annual Report from the Hunter Water Corporation (HWC 2011). However, the largest water utility in NSW, Sydney Water, is not in agreement with these figures and report higher D_t in their Annual Reports (SW 2009, 2011). As with the ACT, this disagreement has reduced in recent years and is converging on approximately a D_t of 200 kL.

Gardner *et al.* (2008) reports the average household demand of 77 kL over the period June to September 2005 from 5300 houses in Brisbane, which when adjusted to an annual estimate is consistent with Stewart *et al.* (2005), the Australian Water Association (AWA 2005) and state averages at this time (Fig. 2-2).

More recently, Willis *et al.* (2011a) monitored water use from 132 Gold Coast households during June 2008 and concludes with a daily per capita water use of 152 L. As expected, this winter estimate is slightly less than the average annual bulk supply at similar times of approximately 190 L (Beal *et al.* 2009; Beal *et al.* 2010; Willis *et al.* 2011b). Adopting an average household occupancy of 2.56 persons (BoS 2009) gives a D_t of 180 kL, which is in agreement with the state average (Fig. 2-2); utility production report in Hervey Bay (Turner *et al.* 2010); but less than measurements from a large five-person Brisbane home (Lucas & Coombes 2009a) and utility production reports for Bundaberg (McLaughlin 2011), where rainfall is more seasonally dominant. Currently (winter 2012), daily per capita water use for South East Queensland is 150 L (QGQWC 2012), which is less than half the consumption at the start of the Millennium Drought. Collectively, these studies indicate D_t in Queensland is just below 200 kL and generally consistent with the ACT and NSW estimates.

Estimates of D_t in Adelaide during the Millennium Drought (Fearnley *et al*. 2004; SA 2004; Barton & Argue 2005; Hurlimann & McKay 2006) are reasonably consistent with the state average at that time (Fig. 2-2). Also, the state average highly correlates with the NWC estimates. The most recent estimate is 171 kL in Adelaide (SAWC 2011). Therefore, current D_t in South Australia is also similar to the ACT, NSW and Queensland.

Roberts (2005) studies D_t from 93 households of the Yarra Valley Water service area. Over the survey period ending 2004 the median household total daily consumption was 598 L, which is a D_t of 218 kL and in agreement with state averages at this time (Fig. 2-2). Most recent studies (Khastagir 2008; Troy & Spearritt 2008; MW 2011) have shown water use has continued to reduce to current estimates of 130 kL (MW 2012).

Wasimi and Hassa (2011) study D_t from 615 homes in Perth using the Survey of Income and Housing collected in 2007-08 and conclude by relating water use to household disposable income and household size, measured by occupants. A D_t of 468 kL is reported for the average size home, which is slightly higher than the state average in 2008 and significantly higher than the NWC estimates (Fig. 2-2). These results are in agreement with an earlier independent survey of Perth residents which reports D_t is 460 kL for the period 1998 to 2000 (Loh & Coghlan 2003). However, the Water Corporation recently estimated D_t at 269 kL (WC 2011), which is more consistent with NWC reports. Therefore, some confusion surrounds household water use estimates in Western Australia and a midpoint estimate of D_t is adopted of 300 kL.

In conclusion, the current D_t is approximately 200 kL for most states and territories but can range from 130 kL up to 300 kL. Further exceptions include the Northern Territory and Tasmania, where higher state estimates are 450 kL and 350 kL, respectively, but could not be verified by independent research.

2.7 Hydrologic parameters for rooved catchments

A simplified runoff model based on the Rational method (IEAust 2001) is commonly used to estimate discharge from rooves constructed of materials with low porosity.

The model includes an initial abstraction of rainfall through wetting the roof surface and flooding small depressions and dead storages, and a proportional abstraction from continuous leaking, splashing and evaporation. The initial loss Q_{il} (L/6min) can be determined from (2-1) where CR_r is the proportional loss, which is often referred to as a coefficient of runoff (unitless); A is the connected roof area (m^2); P is the precipitation intensity of the current interval (mm/s); P_d is the accumulated precipitation of the current day (mm); and D_{il} is the total daily initial loss depth (mm), which is based on empirical data subsequently discussed.

$$Q_{il} = \begin{cases} CR_r \times P \times A, & P_d \leq D_{il} \\ 0, & \text{otherwise} \end{cases} \tag{2-1}$$

The roof discharge Q_r (L/6min) is then determined with (2-2).

$$Q_r = CR_r \times P \times A - Q_{il} \tag{2-2}$$

Many researchers have measured hydrologic parameters for roofs and their results are summarised (Table 2-5). Initial loss abstraction is typically measured as a depth per rain event or per day. In the proposed research, the later was adopted, as this simplifies the approach by avoiding the disaggregation of rainfall data into separate rain events around a minimum dry antecedent period. The impacts of this decision will be examined as part of the verification of model estimates.

Hoey (1984) studies a limited number of rain events in Adelaide and concludes with CR_r of 0.79 and without defining D_{il}. For minor rain events, D_{il} could be a significant portion of rainfall (Chapman & Salmon 1996). Furthermore, it is typical that distributions of daily rainfall are positively skewed by the high frequency of small events. Consequently, ignoring D_{il} could result in comparatively small CR_r that is bias to small events and erroneous otherwise.

With urban rainwater systems, small rain events (<2 mm) are usually insufficient to provide significant tank inflow, particularly when the requirement of first flush diversion is considered. Furthermore, adopting a small CR_r could reduce the simulated inflow from events that are significant to the operation of the system.

Thus, it would be careless to use CR_r estimates that are bias by lack of initial loss measurements.

Table 2-5 Hydrologic parameters for roofs catchments

Reference	$\boldsymbol{CR_r}$ **(-)**	$\boldsymbol{D_{il}}$ **(mm)**	**Description**
(Hoey 1984)	0.79	-	Measurements from galvanised iron roof in Adelaide (SA).
(Laing *et al.* 1988)	0.96	0.20	Measurements from galvanised iron roof in Wialki (WA).
(Chapman & Salmon 1996)	0.90	0.40	Measurements from corrugated asbestos roof in Sydney (NSW).
(Chiew & McMahon 1999)	0.85	1.0	Measurements from urban catchments in Sydney (NSW), Canberra (ACT), Brisbane (Qld.) and Melbourne (Vic.).
(Goyen & O'Loughlin 1999)	0.80	0.50	Measurements of roof runoff from a catchment of 12 allotments in Canberra (ACT).
(Ragab *et al.* 2003)	-	0.50	Measurement from rooves with various pitch and aspect in Wallingford, UK.
(Liaw & Tsai 2004)	0.82	-	Measurements from five rooves of concrete or iron materials in Tiawan.
(Mitchell *et al.* 2008a)	0.85	0.10	Mean values adopted in normal distribution of parameter values.
(Boulware 2009)	0.85	0.40[a]	Application of measurements in Adelaide (SADEA 1980).
(Farreny *et al.* 2011)	0.95	0.80	Measurements from clay tiled rooves in Spain. Other roof surfaces also studied.
(van der Sterren *et al.* 2012)	0.22	-	Measurements from two sites: Zincalume and ceramic tiled rooves in Sydney (NSW).

[a] based on a rate of 2 mm/month and assuming a nominal five rain events per month.

Laing *et al.* (1988) measured roof runoff over a twenty month period from July 1985. The site was located in Wialki, in the Northern Wheatbelt of Western Australia and comprised a 600 m^2 galvanised iron gable roof with an east-west ridge and slope of 20°. Over this period, 248 mm of runoff was recorded from 282 mm of rainfall, which is less than the rainfall expected as the annual average is 316 mm (BoM 2012d). Also, daily rainfall observations ranged from 0.2 to 17.6 mm. Collectively, the low annual rainfall and low rainfall intensity is not typical of conditions in most Australian cities. Consequently, the estimated runoff losses were comparatively low, with CR_r and D_{il} reported as 0.96 and 0.2 mm, respectively.

Furthermore, the size of this roof is uncharacteristic of common urban rainwater systems. Large rooves can be more effective for roof water collection, providing their shape is not too irregular and guttering and downpipes are adequately sized. This is based on the principle of a reduced perimeter area ratio and the presumption that most losses occur around the roof perimeter from splashing and spilling into gutters. Consequently, adopting the loss parameters reported would result in overestimates of roof runoff and rainwater yield, together with potential underestimates of overflow from the whole system.

Chapman and Salmon (1996) measured roof runoff for the period 22nd January to 1st May 1995. The site was located at Kangaroo Point, south of Sydney and comprised a 28 m^2 corrugated asbestos gable roof with east-west ridge and slope of 22°. Throughout the experiment, 26 rain events were detected with a depth of 1 mm or greater. With smaller events, the magnitude of evaporation and runoff was similar. The study concludes by recommending CR_r and D_{il} values of 0.9 and 0.4 mm, respectively, for the Sydney region.

These results are reasonable as CR_r is less than measurements from large roofs in regions of low rainfall intensity (Laing *et al.* 1988) but also greater than measurements where D_{il} has been disregarded (Hoey 1984; Liaw & Tsai 2004; van der Sterren *et al.* 2012). Furthermore, the results are relevant as the location, roof area and configuration is typical of urban residential settings.

Larger connection portions of residential rooves are also common; however, based on previous discussion, a smaller roof would provide a conservative estimate of runoff. Finally, these results are also consistent with recent measurements from metal rooves in Spain (Farreny *et al.* 2011), where rainfall intensity is of similar magnitude.

Goyen and O'loughlin (1999) measured roof runoff from a small estate of 12 allotments in Canberra. Observations were taken from January 1993 to December 1995. This was an extremely wet period, with 24 significant events recorded with average recurrence intervals greater than one year. The roof runoff results focus on one rain event which has a recurrence interval of 2.5 years. CR_r and D_{il} were reported of 0.8 and approximately 0.5 to 1.0 mm, respectively. Unfortunately, comments on the extent of perimeter splashing or gutter overflow were not given, which could have explained these high losses reported. In the absence of measurements of roof splashing in the literature, it may be necessary to include an upper limit on permissible roof runoff in the simulation model and this will be determined by the conveyance capacity of commonly used guttering system.

Liaw and Tsai (2004) measured runoff from five roof types in Taiwan between March and December 2000. Over this period, 100 storms were observed. Roof configurations comprised level concrete; and iron gable, parabolic and saw-tooth designs. The study concludes by recommending a CR_r of 0.82 for all roof types studied. This value is consistent with (Hoey 1984), where quantifying D_{il} was not considered but as previously stated, the coefficient would be larger if initial losses were included.

Furthermore, Liaw and Tsai (2004) confirm earlier theories that simulated results of rainwater tanks are more sensitive to CR_r in scenarios with limited tank volume (Liaw *et al.* 1997). This is expected to be related to the short critical period and the inherent high frequency of spilling and emptying. These results indicate the importance of accurate parameter values in simulating roof runoff.

The most recent measurements of roof runoff are reported by van der Sterren *et al.* (2012). The study monitored two sites in Western Sydney from 1st October 2008 to 6th October 2009. However due to equipment failure, CR_r were reported only for the site comprising a 144 m^2 Zincalume © roof. Unfortunately, details were not provided for roof aspect; guttering system; and devices for leaf separation and first flush. The study concludes with a weighted average CR_r of 0.22 and a distribution of CR_r by rain event average recurrence intervals, or alternately described as rainfall intensity from the 5 minute average maximum burst. As described earlier, the absence of D_{il} estimates introduces bias towards very minor rain events that frequently occur and may not produce tank inflow due to first flush diversion. Thus, a significant underestimate of runoff from events that are crucial to the operation of a rainwater system could occur. Also, excessive overflows could be simulated from events with recurrence intervals greater than one week and this would prohibit accurate assessment of the efficacy to restore aspects of pre-urban stream flow.

Another conclusion of van der Sterren *et al.* (2012) was that the CR_r increases with rainfall intensity, which to some extent is expected as the storm duration is comparatively short and the effects of proportional losses are reduced. However, with roof catchments, significant losses can occur at the perimeter under very high intensity rainfall. Thus, CR_r should eventually reduce and this was not reported. An explanation could be found in the limited intensity of storms during the experiment. The most intense storm was 19.2 mm/hr with an ARI of only one month. Due to results being limited by the range of storms and a disregard for measuring D_{il}, insufficient data has been reported to completely define the response of CR_r to rainfall intensity. Therefore, this relationship will not be included in the model but further research in this area is recommended.

In conclusion, a fixed CR_r of 0.9 and D_{il} of 0.4 mm/d, as reported by Chapman and Salmon (1996), was adopted in the proposed research.

2.7.1 Aspect of connected roof area

The aspect of the connected roof can affect the volume of roof runoff. The leeward side of a high pitch roof can produce significantly less runoff during light rainfall and high winds. Chapman & Salmon (1996) report the windward roof aspect can contribute more than 60% of total roof runoff, where the roof pitch is relatively shallow (22°). Where possible, the direction of prevailing winds should be considered when selecting the connected roof area. The effect of selecting the leeward roof aspect could result in a runoff coefficient that is less than the adopted value of 0.9. For the case previously mentioned, the runoff coefficient for the leeward roof would be 0.72. The effect of reduced runoff coefficients will be investigated in the yield sensitivity analysis of conventional rainwater tanks in Chapter 3.

2.7.2 Gutter hydraulic capacity

In urban Australia, roof drainage systems usually comprise a metal gutter and PVC downpipes which discharge roof runoff into a rainwater tank or the street drainage system. Tank overflow and stormwater from all urban surfaces is prohibited from entering the sewer. Roof drainage systems may also include first flush diverters together with leaf separators mounted on downpipes or between the roof and gutter.

In addition to modelling roof runoff, the hydraulic limits of roof drainage systems should be investigated, which is referred to as the gutter hydraulic capacity G_{hc} (L/s). The occurrence of high intensity rainfall is not limited to large storms that typically overwhelm rainwater storage, but rather small isolated bursts can occur and may partially fill the tank and exceed G_{hc}. Thus, by defining a maximum G_{hc}, overestimates of yield and underestimates of system overflow may be avoided.

G_{hc} can vary significantly and is mostly affected by the quality of workmanship, frequency of maintenance, gutter type, extent of debris and location and size of downpipes. Currently, insitu measurements of G_{hc} are limited to those discussed in Section 2.7 and in most cases, descriptions of gutters and downpipes are very limited. Thus, further research may be necessary to adequately define insitu G_{hc}.

However, an Australian Standard exists for the hydraulic design of gutters and downpipes (AS 3500.3 2003). Also, application of the British Standard (BSPL 2000) is demonstrated by Arthur and Wright (2005). In accordance with the Australian standard, to prevent significant inconvenience or injury to people or damage to property, eaves gutters shall contain roof runoff from a rain event with an ARI of 20 years; and box gutters shall contain the ARI 100 year event. Unfortunately, despite the standard, gutter surcharge can be frequently observed during fairly low intensity rainfall in many urban areas. Poor hydraulic performance can be attributed to a limited understanding and incorrect application of the standard by installers as well as other aforementioned factors.

Given the absence of suitable field data and the knowledge of vast inconsistencies in G_{hc}, a nominal coefficient of efficiency of 0.9 (Arthur & Wright 2005) will be applied to G_{hc} which is calculated from the Australian standards. A yield sensitivity analysis will demonstrate the significance of G_{hc} and the rationale for further research.

By observation, new residential dwellings in Queensland are mostly fitted with Quad slotted hi-front, slotted Trimline or Quad 150 gutters which have effective cross-sectional areas A_e of 5285, 6244 and 8910 mm^2, respectively (Lysaght 2011). These gutters are also installed throughout southern states due to aesthetics and the economics of design. Where additional G_{hc} is needed, mainly to reduce the number of downpipes, the larger gutters are installed. Adopting the typical gradient of 1:500 or steeper, the G_{hc} of these gutters is 1.4, 1.7 and 2.7 L/s, respectively (Fig. 2-3).

The catchment area per downpipe A_c (m^2) can also be determined (Fig. 2-3) and is shown (Table 2-6) where the design rainfall intensities ($^{20}I_5$) are as published in AS 3500.3. Under these parameters, the rainwater tank catchment area is severely limited by gutter capacity unless multiple downpipes can be connected.

Table 2-6 Adopted gutter capacity and catchment area per downpipe

City	$^{20}I_5$ (mm/hr)	Gutter	A_e (mm^2)	G_{hc} (L/s)	A_c (m^2)
Adelaide (SA)	120	Quad Hi-front	5285	1.4	40
Brisbane (Qld.)	250	Trimline	6244	1.7	25
Canberra (ACT)	200	Trimline	6244	1.7	30
Darwin (NT)	370	Quad 150	8910	2.7	25
Melbourne (Vic.)	130	Quad Hi-front	5285	1.4	37
Perth (WA)	140	Quad Hi-front	5285	1.4	35
Sydney (NSW)	210	Trimline	6244	1.7	30

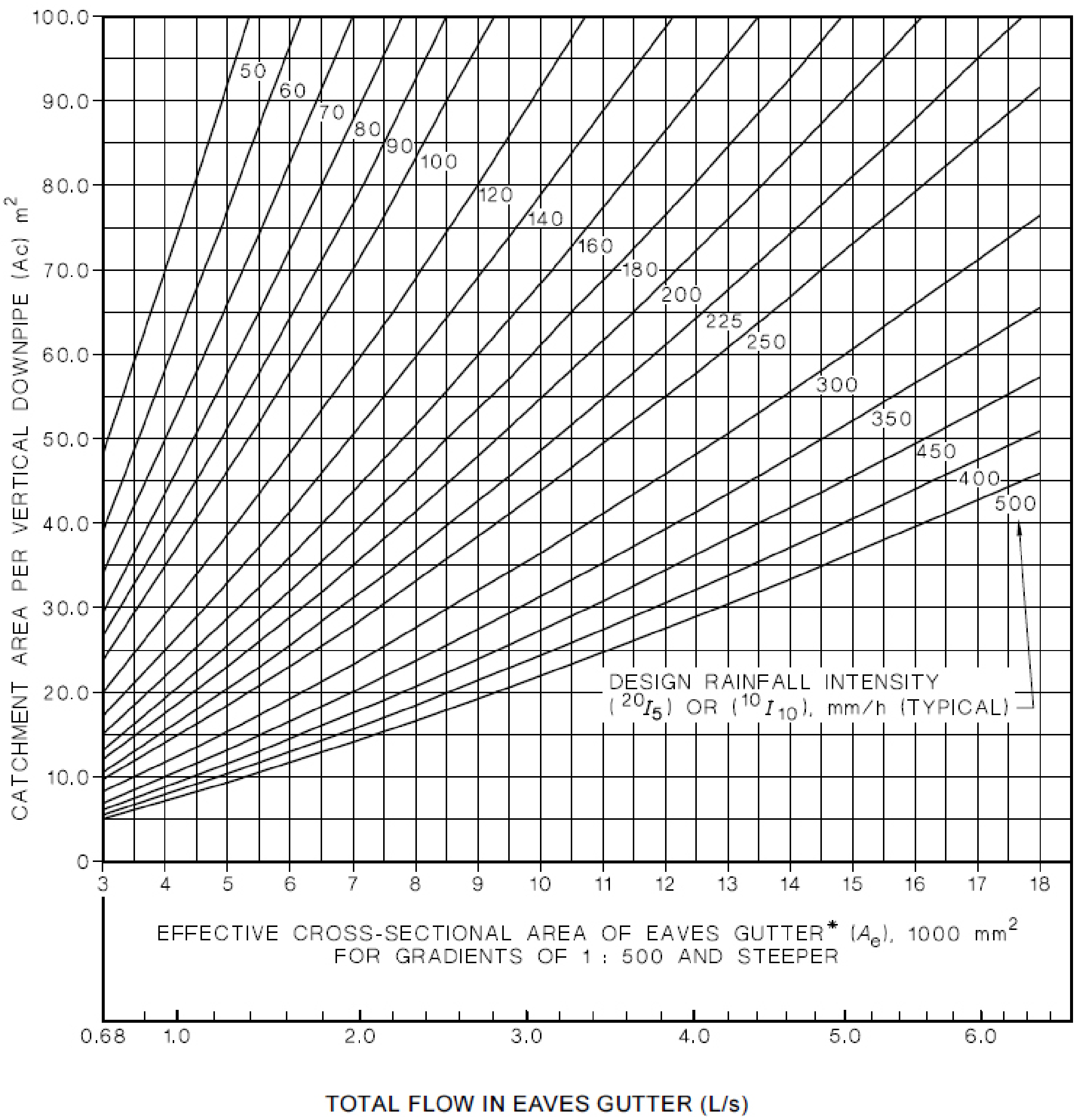


Fig. 2-3 Required size of eaves gutters for gradients of 1:500 and steeper. Source: (AS 3500.3 2003)

2.7.3 Leaf screen hydraulic efficiency

Leaf screening devices are used to remove gross pollutants from roof runoff mainly consisting of leaves, sticks, faecal matter and other debris. There are many approaches to separate debris from roof runoff, with designs principally based on screening at the gutter or downpipe (Fig. 2-4). White (2009) reports that 50% of surveyed rainwater systems in South East Queensland installed one of these methods of screening.

Gutter mounted screens are more prone to clogging due to limited self-cleaning from low flow velocity and low screen inclination. Due to recent improvements in design, downpipe mounted separators are commonly fitted to new dwellings in low debris areas, as they offer superior durability, serviceability and performance.

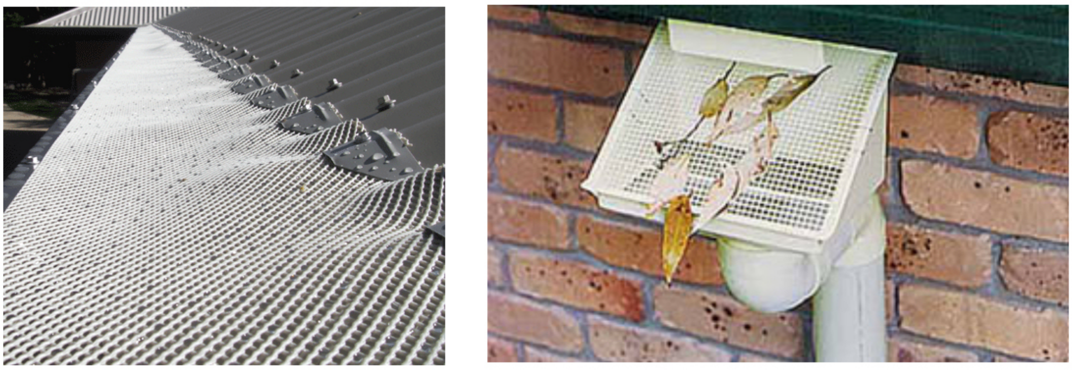


Fig. 2-4 Leaf separators mounted on gutter or downpipe. Original source unknown.

Due to the absence of data in the literature on the hydraulic efficiency of leaf separators, flow diversion from leaf separators will be disregarded from the water balance simulation and the impacts of this decision will be apparent when model estimates are verified.

2.7.4 First flush devices

A consistent portion of runoff is not always treated in rainwater systems as the total runoff volume is unknown and varies. The first flush portion can potentially range from 0.5% to 100%. The former represents a first flush depth D_{ff} of 0.25 mm/d for a typical sized roof catchment (100 m^2) and rainwater tank (5 kL), filling in a single day's rain. This scenario is less likely to occur than the latter, when the daily rainfall is not greater than D_{ff}. Furthermore, a suitable D_{ff} can be difficult to detect when the time of concentration of the catchment is similar to the storm duration which can regularly occur on micro catchments (Brodie 2007).

First flush devices consist of a small chamber that captures a predetermined volume of runoff and diverts excess flow to rainwater storage. The devices can be located on downpipes or at the rainwater tank inlet. They have the basis that the highest concentration of pollutants occurs in the earliest portion of runoff as the roof is washed and pollutants are progressively removed (Quek & Förster 1993; Van Metre & Mahler 2003; Egodawatta et al. 2009). The flush capacity is renewed by slowly releasing captured runoff by discharging into a subsurface infiltration bed over 24 hours and in most cases without treatment. This allows the first flush depth D_{ff} (mm/d) to bypasses the rainwater tank and reduces the tank pollutant loads. The typical arrangement of first flush devices normally includes a floating barrier to bypass flow once the initial portion of runoff is contained (Fig. 2-5).

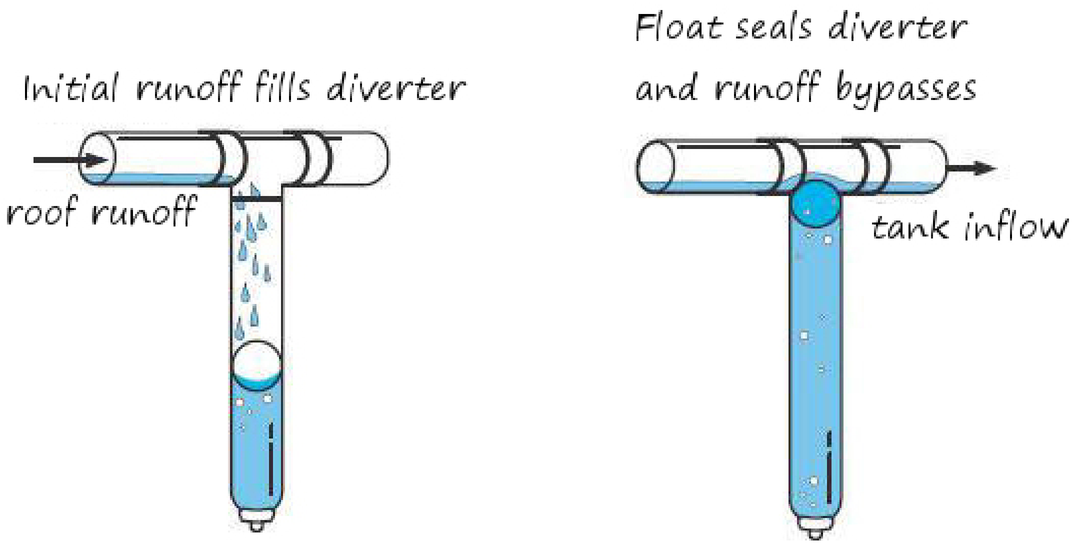


Fig. 2-5 Rainwater harvesting first flush device. Original source unknown.

Mechell (2009) investigates the affinity of common first flush arrangements to inhibit interaction between containments and bypass flow, and concludes with no discernible advantage from any one arrangement. This is a surprising result, as not all scenarios included a floating barrier. It was perceived this barrier would reduce the disturbance of containments in the upper regions of the first flush device and reduce interaction with bypass flow.

Justification for these results may be found in the use of a diversion junction with a restricted diameter, which itself could partially act as a fixed barrier and may lessen the advantage of the floating alternative. Restricted diversion junctions are not common in Australia and the floating barrier arrangement is near universal. With no disadvantage reported in Mechell's study, current practices are presumed favourable.

Bach *et al.* (2010) is working towards statistical approaches to define first flush volumes to restore background levels of contaminants from the catchment. However, it is more common to assess the first flush effectiveness through compliance with drinking water guidelines of samples taken from first flush containments and rainwater tanks (Coombes *et al.* 2000).

Rainwater quality can usually be improved by diverting a larger portion of runoff into the first flush device. However, this can reduce rainwater yield and limit the reliability of rainwater tanks. It was recently shown by removing a small first flush devices rainwater yield could increase by at least 5% (Lucas & Coombes 2009a). Therefore, a compromise exists between improved water quality and reduced rainwater supply reliability.

Without regular cleaning, first flush devices and filters can clog, fail to drain and cease to operate. This can be counterproductive as conditions could become favourable for breading bacteria and mosquitoes. Moreover, containments may mix with runoff and degrade harvest quality in subsequent rain events. To prevent this, electronic timers can be used to periodically drain first flush devices. This approach avoids filters and small apertures, however, adoption is rare and was not reported in recent surveys of rainwater systems (White 2009).

The effectiveness of first flush devices for rainwater tanks have been studied for at least thirty years (Table 2-7).

Table 2-7 Measurements of first flush diverters for rainwater tanks

Source	Key results	Study region
(Jenkins & Pearson 1978)	D_{ff} of 0.25 mm/d is mostly suitable.	California
(Yaziz *et al.* 1989)	D_{ff} of 0.05 mm/d should safeguard against microbiological contamination but not heavy metals. Dry antecedent period and rainfall intensity affect performance.	*unknown*
(Coombes *et al.* 2000)	D_{ff} of 2 mm/d was insufficient for potable water standards.	Newcastle (NSW)
(Wade 2003)	D_{ff} of 2 mm/d should meet most potable water standards.	Brisbane
(enhealth 2004)	A 20 to 25 L diversion from the average sized roof is suitable for non-potable use.	Temperate, subtropical and tropics
(Gardner *et al.* 2004)	D_{ff} of 1 to 2 mm/d is recommended.	Brisbane
(Martinson & Thomas 2004)	D_{ff} of 0 to 8 mm/d is necessary to achieve turbidity treatment under various conditions.	Various countries
(Krishna 2005)	D_{ff} of 0.4 to 0.8 mm/d diversion is suitable for most typical households.	Austin, Texas
(QDIP 2007a)	A 20 L first flush as a minimum for non-potable use.	Queensland
(SA 2008)	A 20 L first flush as a minimum for non-potable use.	National
(Schriewer *et al.* 2008)	93% of measured runoff events displayed first flush behaviour.	Munich, Germany
(Boulware 2009)	D_{ff} of 0.5 to 8 mm/d depending on contamination levels associated with rainfall frequency, adjacent trees and airborne constituents.	Austin, Texas
(Mechell 2009)	Common first flush arrangements have an affinity for inhibiting interaction between containments and bypass flow.	Austin, Texas
(Wang & Li 2009)	First flush is most effective on long smooth rooves with a steep gradient.	*theoretical*
(Kus *et al.* 2010)	D_{ff} of 2 mm/d is suitable for drinking water in most cases.	Sydney
(WHO 2011)	20 to 25 L to bypass the cleaning wash of water from entering water storage.	Global
(Mendez *et al.* 2011)	D_{ff} of 0.4 mm/d should be suitable for non-potable supply.	Austin, Texas

A significant range in D_{ff} is reported (0.05 to 8 mm/d) and is driven by factors including target water quality; frequency and intensity of rainfall; degree of contamination from adjacent trees and peripheral pollutant sources; duration of dry antecedent period; and characteristics of the roof including material, surface roughness, slope and aspect.

Early investigations (Jenkins & Pearson 1978; Yaziz *et al.* 1989) report low D_{ff} of 0.05 to 0.25 mm/d is suitable for non-potable end use, providing contamination by heavy metal and debris is not excessive. Recently, minimum first flush volumes of 20 to 25 L were recommended by the Australian Federal Department of Health and Ageing - Environmental Health (enhealth 2004), the Queensland Development Code (QDIP 2007a), the National Design Standards for rainwater tanks (SA 2008) and the World Health Organisation (WHO 2011). Consequently, it is typical to find first flush diverters of this volume regardless of the connected roof area, which in high density developments can be less than 100m^2 (White 2009). Therefore, D_{ff} could be as high as 0.4 mm/d.

Krishna (2005) and Mendez *et al*. (2011) agree that a D_{ff} of at least 0.4 mm/d should be suitable for non-potable end use, which is based on American guidelines (TWDB 2005). These results from Austin, Texas, are relevant as the American standards for water reuse (USEPA 2004) is reasonably consistent with the Australian drinking water guidelines (NHMRC 2010), and the average annual rainfall of Austin (850 mm) is consistent with many Australian capital cities. Also, these results are consistent with adopted practices.

Martinson & Thomas (2004), Kus *et al*. (2010), and Mendez *et al*. (2011) were in agreement that turbidity was the critical parameter which consistently exceeded guidelines for water use. In some cases, for full compliance a D_{ff} of 8 mm/d was required. This is excessive and would significantly reduce rainwater supply reliability, and is not recommended for non-potable use.

Coombes *et al*. (2000) monitored rainwater quality in a small residential development in Newcastle over the period of July to August 1998, when 40 rain events were observed. The development was designed with a D_{ff} of 2 mm/d which is consistent with recommendations from independent studies (Wade 2003; Gardner *et al.* 2004; Kus *et al.* 2010). Rainwater was mostly compliant with Australian drinking water guidelines and was of higher quality than first flush containment. However, further investigations revealed not all first flush diverters were constructed and underground tanks were poorly sealed, which enabled direct ingress of soil and other pollutants. These construction errors created a challenging situation and the results obtained are thereby a worst case scenario.

The Newcastle study demonstrates the significance of proper construction, especially for underground low pressure infrastructure. Fortunately, rainwater tanks and first flush devices are mostly above ground in urban residential Australia, and this arrangement is less susceptible to contamination. Therefore, a D_{ff} of 2 mm/d is considered excessive for non-potable urban rainwater systems.

Schriewer (2008) studied the runoff quality from a 14 year-old zinc coated roof in Munich, Germany. This research is relevant as zinc coated roof sheeting, such as Zincalume © and galvanised steel, can be found in urban areas throughout Australia. Thirty-eight runoff events occurred over the twelve month study period commencing May 2004. Average results showed a steep decline in zinc concentration for the first 20 minutes; a gradual decline up to one hour; and, for the most part, stable conditions thereafter.

These results demonstrate some benefit for first flush bypass from zinc coated rooves, however, a bypass volume or depth was not recommended. Also, results were rarely compliant with drinking water guidelines. This is not surprising, given Schriewer's work is essentially assessment of leachate from a quasi-unlimited supply of zinc, and the mass volume curves would be uncharacteristic of transportation of insoluble debris and faecal coliforms commonly found on rooves. Yaziz (1989) arrives at a similar conclusion. Nevertheless, heavy metals are among the constituents of roof runoff with high health risks and should be treated by first flush devices where practical.

Heavy metals, such as lead and zinc, are reported to precipitate into the sludge zone of rainwater tanks (Magyar *et al.* 2007; Huston *et al.* 2012). This zone is located below the outlet and allows sedimentation to occur with limited disturbance from normal abstraction. Also, Huston *et al.* (2012) reports that lead concentrations were consistently lower in rainwater tanks where first flush devices were fitted.

Kus *et al*. (2010) measures runoff quality over a three month period commencing November 2008 from a thirty-year old house with a concrete tiled roof. The house was located in South-West Sydney and in close proximity to an industrial precinct and freeway. The roof characteristics are typical of many urban households in Australia and close proximity to peripheral pollutant sources offers challenging conditions (Van Metre & Mahler 2003). However, prevailing wind and other climatic factors can significantly alter pollutant loads from periphery sources (Evans *et al.* 2006) and these conditions were unfortunately not stated. Evans *et al.* (2009) also states that the oligotrophic tank conditions may be favourable for inhibiting development of organisms of faecal origin.

It was demonstrated, in these conditions, a D_{ff} of 2 mm/d can achieve water quality that is substantially compliant with the Australian drinking water guidelines. A D_{ff} of 5 mm/d was necessary for full compliance, given high turbidity and concentrations of lead. However, in most urban residential cases, rainwater is supplied to non-potable end uses where water quality constraints are less stringent. Therefore, as previously stated, a D_{ff} of 2 mm/d would be excessive.

Based on these studies, a D_{ff} of 0.4 mm/d or 40 L / 100 m^2 / d is recommended for non-potable rainwater systems and was adopted for the proposed research.

2.7.5 Roof characteristics

Many studies have also looked at what conditions are most favourable for first flush devices. Mendez *et al*. (2011) measures runoff quality in 2009 from pilot-scale and full-scale residential rooves in Austin, Texas. Roof types included asphalt fibreglass shingle, metal, concrete tile, green and bituminous membrane. Overall, rooves constructed from metal, concrete tiles or bituminous membrane provided encouraging results. Furthermore, the lowest concentrations of faecal coliforms were recorded from metal rooves and this is suggested to correlate with high surface temperatures from metal emissivity. Excluding bituminous membrane, these materials are commonly used for roof construction throughout urban Australia.

Wang and Li (2009) studied the theoretical relationships between roof characteristics and first flush effectiveness by applying the kinematic wave model and a modified pollutant erosion equation. Unfortunately, results are not directly verified by empirical data, however, some results are consistent with verified findings by others (Pitt 1987; Kang *et al.* 2006). In theory, first flush treatment is most effective on smooth rooves with a long (20 m) and reasonably steep catchment (20 ° pitch). The roughness, roof length and pitch investigated are consistent with the characteristics of urban roofs in Australia.

Therefore, collectively, these studies demonstrate current practices in urban Australia for design and installation of rainwater systems are potentially the most conducive for effective first flush of pollutants, considering the roof materials, arrangement of first flush devices and roof geometry.

Chapter 3 Study Scope and Context

The study scope of the dissertation is defined by the results of the literature review and a yield sensitivity analysis of conventional rainwater tanks. The chapter concludes by outlining potential methods for implementing adaptive management of environmental flows from rainwater tanks.

3.1 Introduction

The context of urban residential rainwater harvesting was outlined in Chapter 1 and a review of the literature pertaining to simulation of rainwater systems and their adoption in the WSUD field was presented in Chapter 2. As the research hypothesis examines the volumetric performance of rainwater tanks, the assessment of water quality or catchment scale implications is precluded. To refine the research scope further, the results of the literature review will be discussed and a yield sensitivity analysis of conventional rainwater tanks is presented. Finally, the extent of simulation scenarios and potential operating conditions are outlined for the rainwater tanks studied.

In this chapter knowledge gaps are identified from the outcomes of the literature review and the results of a yield sensitivity analysis. These knowledge gaps were synthesised and categorised to form the interdependent research topics of the dissertation and the overarching phases of the research methodology.

Phases of the dissertation research methodology include: (1) Establishing a mass-balance simulator of dual-duty rainwater tanks; (2) Establishing and simulating adaptive approaches to rainwater harvesting; and (3) Deriving rapid methods to determine the dual-duty performance of rainwater tanks.

The structure of the dissertation was previously introduced in Chapter 1. The structure is expanded here to illustrate the progression of the dissertation through each research topic (Chapter) and phases of the research methodology (Fig. 3-1, Fig. 3-2 and Fig. 3-3).

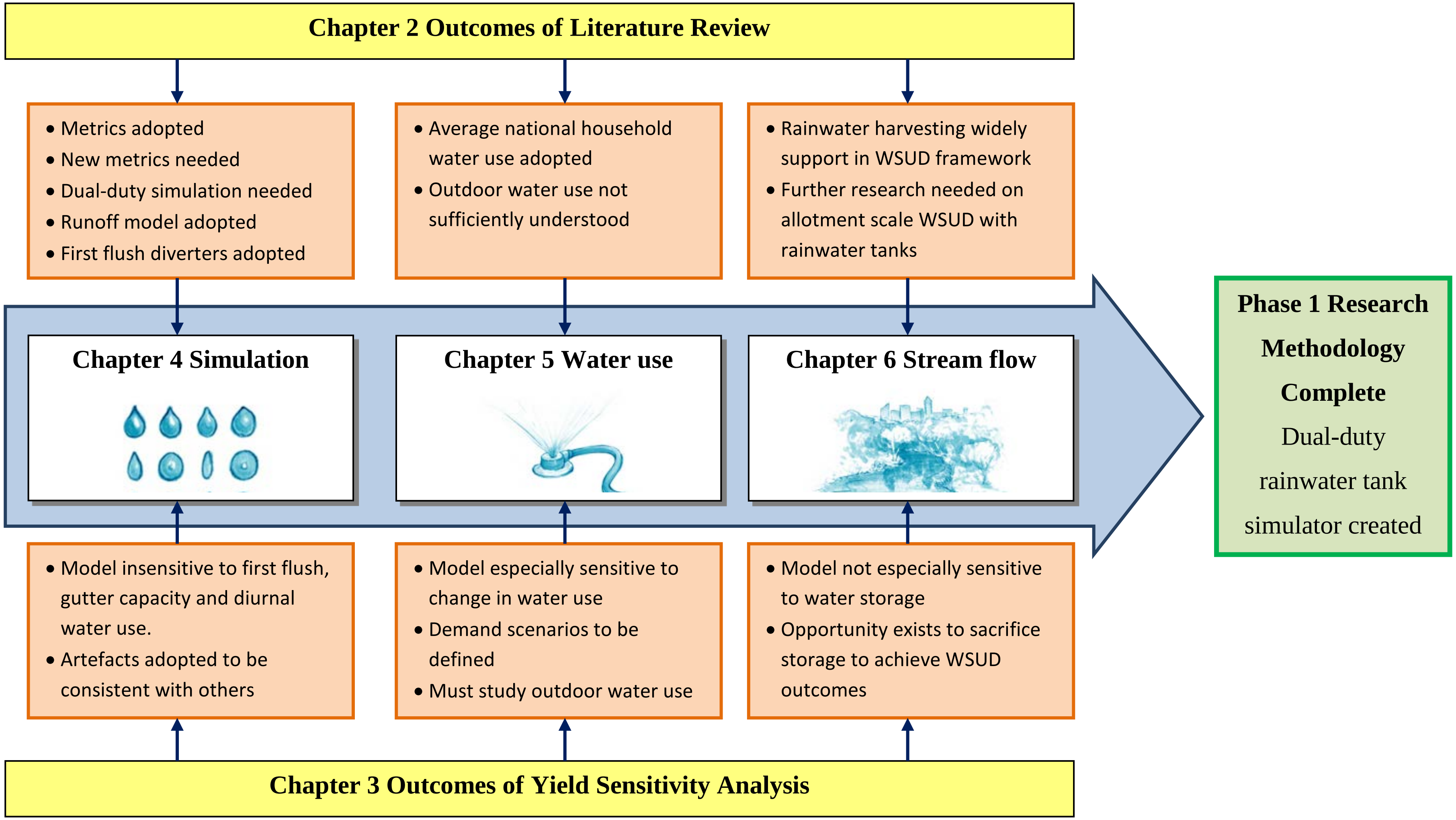


Fig. 3-1 Dissertation Flowchart Phase 1

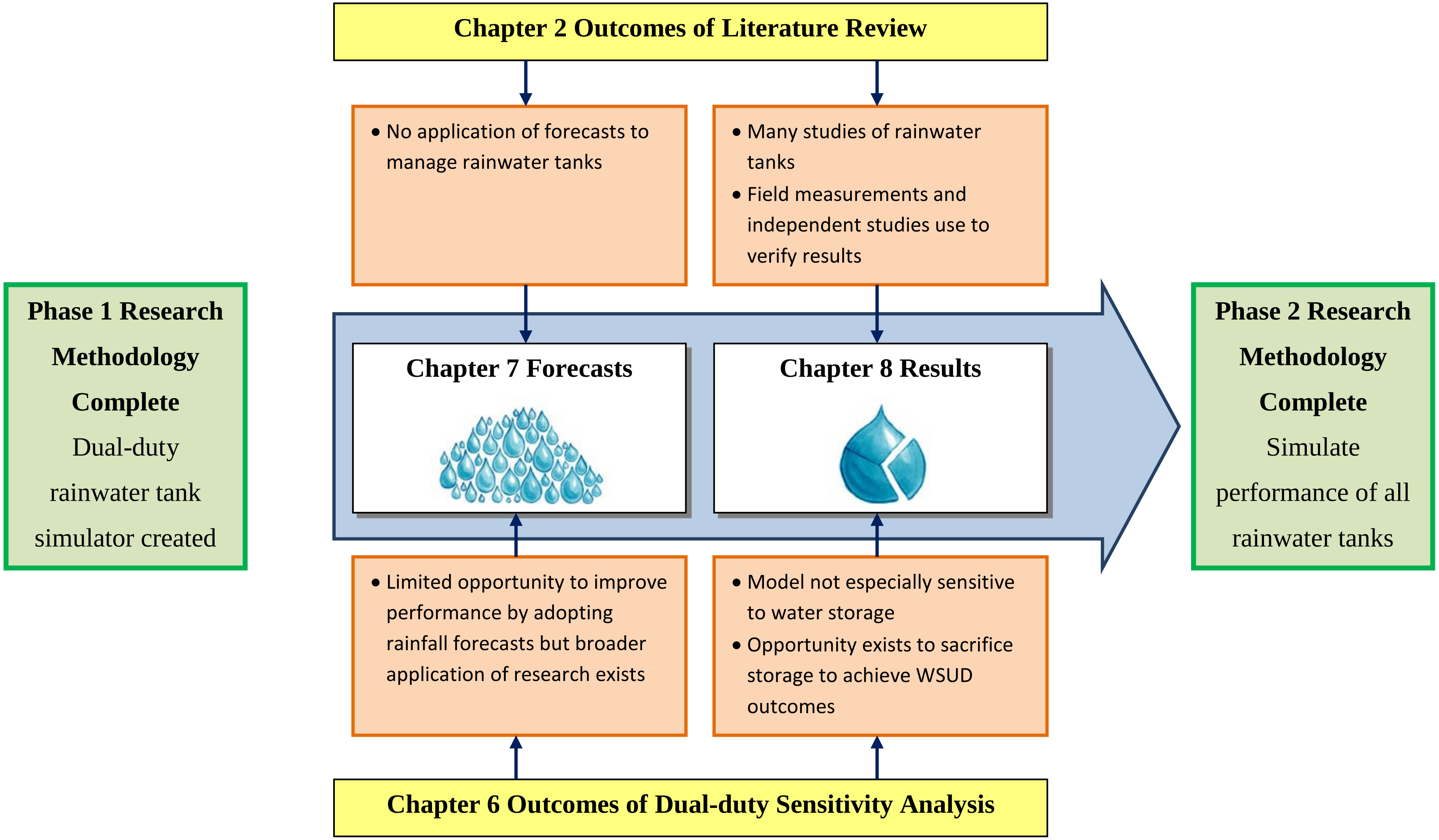


Fig. 3-2 Dissertation Flowchart Phase 2

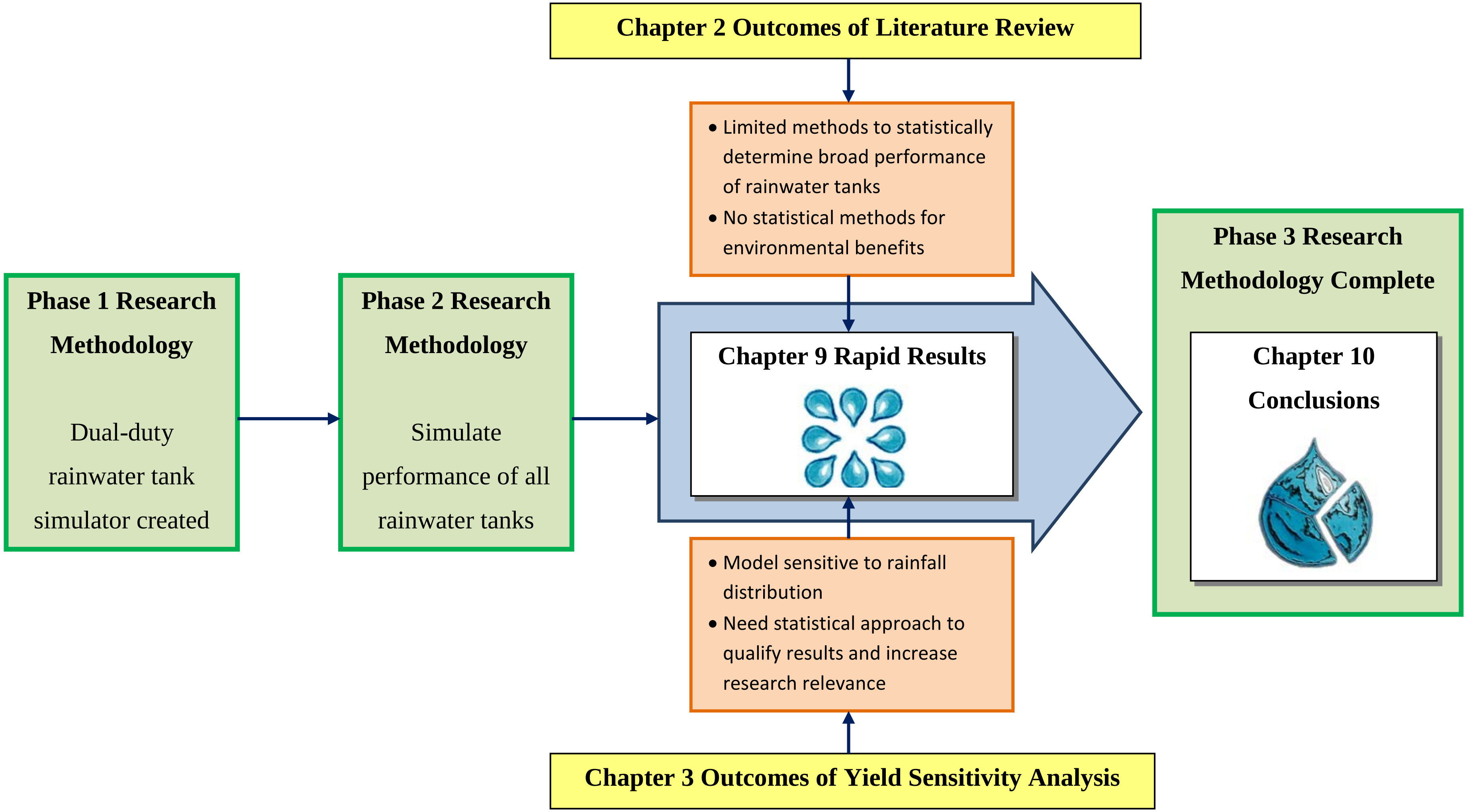


Fig. 3-3 Dissertation Flowchart Final Phase 3

3.2 Outcomes from the literature review

The outcomes of the literature review are aggregated into the early topics examined in the dissertation.

3.2.1 Simulation

The metrics applied to study the performance of rainwater tanks were reviewed and recommendations were made to develop a new measure of water supply performance and the overall dual-duty performance of rainwater tanks. These new metrics are fundamental to the research. Some metrics were adopted from the literature (Table 3-1).

Table 3-1 Metrics adopted from the literature

Metric	Description
Average annual household rainwater yield **Y** (kL)	A component of the system water balance and will be applied to verify model estimates and examine model sensitivity in this chapter
Average annual rainwater system overflow **O** (kL)	A component of the water balance and used in conjunction with the environmental benefit index
Average annual environmental flow **EF** (kL)	The final component of the tank water balance
Average annual imported water **IW** (kL)	A measure of dependence on reticulated water supply

Numerous models for simulating rainwater tanks were reviewed with none of the software packages capable of modelling dual-duty and adaptive rainwater tanks in their current form. PURRS was the preferred package, however modifications are needed to simulate operating rules for the adaptive management of environmental flow. Unfortunately, the PURRS model was not made available for this research. Therefore, a purpose built model is established and the development, calibration and verification of the model is also fundamental to the research.

Empirical studies of roof hydrologic parameters were reviewed and a simplified runoff model comprising a runoff coefficient CR_r of 0.9 and depth of initial loss D_{il} of 0.4 mm was recommended. The runoff model is applied in the simulation of rainwater systems. The sensitivity of estimates of rainwater yield to these parameters will be examined in this chapter. Moreover, investigation of these parameters will limit uncertainty, increase the relevance of results and provide some insight into the implications of roof characteristics. Such characteristics include pitch, orientation and aspect of connected area to prevailing winds (Chapman & Salmon 1996; Ragab *et al.* 2003; Lancaster 2006; Farreny *et al.* 2011).

The maximum hydraulic capacity of common gutter profiles and corresponding connected roof areas was examined and these parameters will be included in the yield sensitivity analysis in this chapter. Also included, is the assumption of 100% hydraulic efficiency of leaf separators, due to the absence of data in the literature; and the application of daily initial losses from the roof catchment, to avoid identifying separate rain events. The impacts of these model artefacts will be examined in the yield sensitivity analysis to qualify model estimates.

Extensive applications and guidelines for first flush devices were reviewed and a first flush depth D_{ff} of 0.4 mm/d or 40 L / 100 m^2 / d was recommended for rainwater tanks exclusively supplying non-potable end uses. First flush devices should be included in the simulation of rainwater tanks and the sensitivity of yield estimates to first flush depth is examined in this chapter.

3.2.2 Water use

Average annual household water demand D_t was reviewed throughout Australia with current estimates at approximately 200 kL for the average size home in most states and territories but can range from 130 kL up to 300 kL. Further exceptions include the Northern Territory and Tasmania, where higher state estimates are 450 kL and 350 kL, respectively, but these could not be verified by independent research. D_t estimates will be applied in to establish rainwater demand scenarios. As D_t is known to vary both in temporal and spatial aspects, an investigation into the impacts of D_t on rainwater yield will be necessary to identify areas of further research. A yield sensitivity analysis will be examined in this chapter to reveal the important aspects of simulating rainwater tanks.

Furthermore, it is understood that outdoor water use can vary significantly in both temporal and spatial aspects and it will be necessary to establish a relationship to this component of water use to qualify simulation estimates.

3.2.3 Stream flow restoration

The role of rainwater tanks in WSUD was examined with unanimous support discovered in the development and modelling guidelines in all states and territories. Thus, increasing the knowledge of the environmental benefits of rainwater tanks at the allotment scale would be a valuable contribution towards promoting water sensitive cities. As previously discussed, this is achieved by adapting the environmental benefit index discovered from the literature review to the research context.

3.3 Rainwater yield sensitivity analysis

To further refine the scope of research from the outcomes of the literature review, a yield sensitivity analysis of conventional rainwater tanks was undertaken. The analysis will demonstrate the sensitivity of model estimates to the simulation parameters. Parameters which have little to no impact on model estimates may be disregarded from further investigation, while others may require greater scrutiny.

For a rudimentary approach, the analysis was limited to rainwater yield estimations from conventional rainwater tanks. The estimates were derived from a preliminary version of the rainwater simulator presented in Chapter 4. However, the sensitivity analysis will be expanded to include the dual-duty performance of leaking rainwater tanks based on estimates from the final simulator. This dual-duty sensitivity analysis is discussed in Chapter 6.

The preliminary simulator calculated tank inflow from pluviograph observations and estimates from the literature review of roof runoff coefficient, depth of initial loss and depth of first flush. Diurnal water use patterns were also adopted from the literature review and seasonal outdoor water use was estimated from utility production reports. Roof runoff and water use estimates were combined to perform mass-balance simulation and the average annual rainwater yield was determined for the scenarios examined in this chapter.

The sensitivity of rainwater simulation is expected to be non-linear for most parameters, based on observations of rainwater yield curves which approach a horizontal asymptote as tank volume and other parameters increases independently

(Imteaz *et al.* 2012). Therefore, the linear approach of measuring model sensitivity with parameters set to the lower and upper extreme domain may provide misleading results. However, there is a significant variation in the valid domain of some parameters and this should be included in the analysis to consider the potential variation of model estimates (Hamby 1994).

A modified form of the sensitivity index (Hamby 1994) was applied where upper and lower parameter values were permitted to be within or at the extreme domain values. This measures model sensitivity over a limited subset of the domain that represents commonly adopted values, which is similar to the methodology of the local sensitivity analysis (Hamby 1994). With this approach, the potential variation of model estimates was included by standardising the adopted parameter range by the valid parameter domain. Thus, this method introduced here is referred to as the standardised sensitivity index SSI.

The parameter change index ΔP_i (unitless) for parameter i is the portion of the parameter's domain considered, or in other words, the ratio of absolute difference in the adopted parameter values ΔP_{ai} to the valid parameter domain ΔP_{di} and is determined with (3-1).

$$\Delta P_i = {}^{\Delta P_{ai}}/_{\Delta P_{di}} \quad \textbf{(3-1)}$$

The proportional change in model output ΔMO_i (unitless) from independently altering parameter i is determined with (3-2) and used to calculate the standardised sensitivity index SSI_i for parameter i, with (3-3).

$$\Delta MO_i = {}^{(MO_{max} - MO_{min})}/_{MO_{max}} \quad \textbf{(3-2)}$$

$$SSI_i = {}^{\Delta MO_i}/_{\Delta P_i} \quad \textbf{(3-3)}$$

The standardised sensitivity indices were independently derived for parameters relevant to conventional rainwater tanks. To demonstrate the yield sensitivity, a base scenario of parameters was established (Table 3-2), together with commonly adopted parameter ranges expressed as minimum and maximum values, the valid parameter domain, and their corresponding parameter change indices.

Table 3-2 Parameter values for yield sensitivity analysis

	Adopted			Domain		
Parameter	**min**	**base**	**max**	**min**	**max**	ΔP_i
Gutter hydraulic capacity G_{hc} (L/s)	1.4	1.7	1.7	1.4	2.7	0.23
Initial loss depth D_{il} (mm)	0	0.4	1	0	1	1.00
Roof runoff coefficient CR_r (-)[a]	0.72	0.9	1	0.22	1	0.36
Total tank volume V_t (kL)	2.5	5	7.5	2	10	0.63
Connected roof area A_r (mm^2)	100	150	200	25	300	0.36
Average annual external rainwater demand D_{re} (kL)[b]	1	20	43.5	0	230	0.18
Average annual precipitation P (mm)[c]	552	707	973	200	2000	0.23
Average annual total rainwater demand D_r (kL)	44	87	176	20	350	0.40

[a] Lower valid runoff coefficient adopted from van der Sterren (2012).
[b] Upper valid external demand adopted from Willis (2010).
[c] Annual precipitation from 2008 to 2011 pluviograph observations in Melbourne (station 086282), Canberra (station 070014) and Sydney (station 066062) for minimum, base and maximum scenarios, respectively.

The analysis was conducted using a six-minute time interval over a limited simulation period from 2008 to 2011. In many locations annual rainfall over this period was quite high; therefore, yield estimates are not expected to represent the long-term average. The results (Fig. 3-4) are similar to independent analysis (MJA 2007a) and will be presented following the structure of the dissertation, like the outcomes of the literature review.

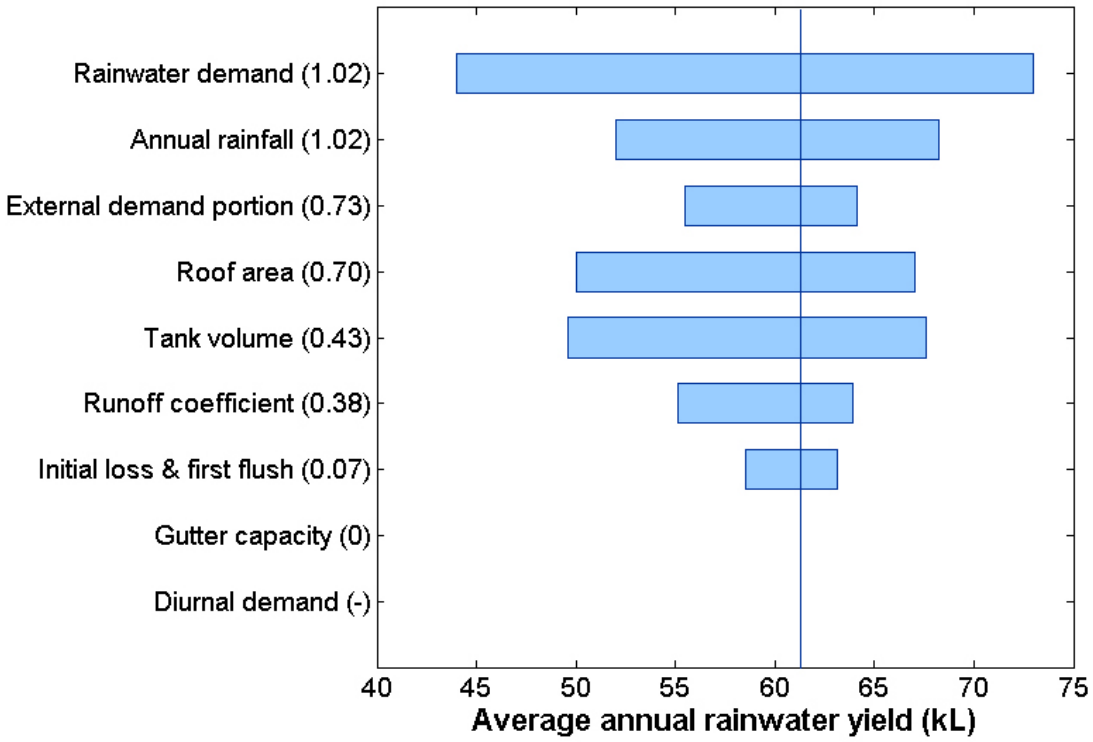


Fig. 3-4 Yield sensitivity analysis of conventional rainwater tanks with SSI values in parentheses

3.3.1 Simulation

Returning for a moment to the literature review, it was discovered that roof runoff may be influenced by the roof aspect. Chapman & Salmon (1996) report the runoff coefficient reduced from 0.9 to 0.72 when connecting only the leeward face of a shallow pitched roof (21°) to the rainwater tank. The parameter sensitivity analysis showed this would reduce yield by 10%, which is significant given the potential for higher pitched rooves. Therefore, it is recommended to connect opposing roof aspects to accommodate for variations in runoff during inclement conditions.

A difference between the sensitivity indices of roof area (SSI = 0.70) and runoff coefficient (SSI = 0.38) demonstrate a limitation with the methodology of the yield sensitivity analysis. These values should be similar as the runoff coefficient scales the roof area. The discrepancy is attributed to a larger valid domain for the roof area. Therefore, the sensitivity analysis results will depend on the methodology used. Notwithstanding this, these results are reasonable for this application and, as previously mentioned, are similar to other independent studies.

Model estimates appear to be relatively insensitive to the initial loss abstraction from the roof and the first flush diversion. This is consistent with independent estimates that rainwater yield increased by only 5% when a small first flush diverter was bypassed (Lucas & Coombes 2009a). However, there is extensive research on first flush devices for rainwater tanks, as summarised in the literature review, and this work is essential for maintaining a balance between maximising rainwater yield and water quality. Therefore, first flush devices will be universally included in the rainwater simulation model.

Model estimates were not altered by changes in gutter hydraulic capacity over the scenarios examined. In this case, rainfall observations were from Canberra where rainfall intensity is comparatively low. Results are expected to vary by location so the maximum gutter hydraulic capacity will be included in the rainwater simulator and overflow from gutters will be combined with tank overflow in performance estimates. This presumption will be verified were model estimates are validated.

Finally, model estimates were not altered by the application of an hourly diurnal pattern which contradicts practices of very fine demand intervals (5 minutes) adopted by others (Coombes *et al.* 2003). Therefore, further investigation of suitable time-steps for the components of rainwater simulation model is necessary to qualify results.

3.3.2 Water use

The results demonstrate model estimates are especially sensitive to change in rainwater demand and rainfall with both parameters recording the highest SSI of 1.02. This means an equivalent proportional change in model output was observed for the portion of the parameter's domain considered. Thus, detailed analysis of household water use is necessary to qualify simulation results and this was previously covered in the literature review.

In consideration of these results, the analysis of household water use will expanded to define demand scenarios based on the split between internal and external water use and the split between internal components. Also, hourly diurnal patterns for internal and external water use will be derived.

Model estimates are also sensitive to the portion of demand allocated to seasonal variation through external use (SSI = 0.73). In these scenarios, the split between internal and external rainwater demand was altered while the total rainwater demand remained constant. Thus, a detailed analysis of the temporal variability of external water use is necessary and should be included in the simulation to qualify results.

3.3.3 Stream flow restoration

Model estimates of rainwater yield are moderately sensitivity to the tank volume (0.43). This demonstrates an avenue exists to sacrifice some water storage for enabling environmental flows and provides rationale for this research. Further analysis of managing storage space will be investigated in a dual-duty performance sensitivity analysis which will follow after the metrics for determining environmental benefits of leaking rainwater systems are defined.

3.3.4 Rapid performance estimation

The results also demonstrate estimates of rainwater yield are unlikely to be consistent in regions with similar annual rainfall, or rainfall seasonality, as the model is especially sensitive to the rainfall observations included. Thus, a rapid method to derive rainwater tank performance from rainfall statistics taken from capital cities together with other system parameters is necessary to increase the relevance of research results.

Model estimates are also sensitive to the connected roof area (SSI = 0.70). Therefore, a range of roof areas should be considered to increase the relevance of results and this range will be defined in this chapter. Also, a rapid method to estimate system performance should include variations in roof area.

3.4 Simulation scenarios

The outcomes of the sensitivity scenarios help define the scope of research. Parameters that describe these scenarios include the connected roof area, tank volume and rainwater demand. Parameter ranges have been established to predominately facilitate analysis of typical residential settings in Australia (Table 3-3).

Table 3-3 Simulation scenarios for urban residential settings

	Scenarios				
Parameter	**Min.**	**Small**	**Base**	**Large**	**Max.**
Connected roof area A_r (m^2)	25	100	150	200	300
Total tank volume V_t (kL)	2	2.5	5	7.5	10
Rainwater demand D_r (kL/y)	20	44	87	176	350

Parameter values based on results of Chapter 4.

3.5 Potential operating conditions for leaking and adaptive systems

As mentioned in Chapter 1, at this stage there is no evidence of applying the operating practices of large-scale reservoirs to residential rainwater tanks as the low-technology status quo of rainwater tanks prohibits automating such an approach. However, to discover the full potential of rainwater tanks, it is assumed that automation could be economically achieved by an electronic monitoring and control device.

Operating rules for the release of water from reservoirs can be very complex (Ganji *et al.* 2007; Chaves & Chang 2008; Celeste & Billib 2009) considering objectives may include maximising hydropower output or balancing storage between a network of reservoirs for various uses and ecological needs. However, fundamentally, these operating rules are based on the hydrologic conditions comprising current storage, current inflow, forecasted inflow, current demand and forecasted demand (Hejazi *et al.* 2008), together with minimum downstream human and ecological requirements. Some of these conditions can be disregarded with the rainwater harvesting context.

3.5.1 Simulation

Inflow into a rainwater tank is comparatively flashy with a limited duration. Moreover, the ratio of inflow to storage is often significantly higher for rainwater tanks. Therefore, current inflow is not anticipated to be a critical factor and can be disregarded.

3.5.2 Water use

The critical period, defined as the time from full to empty without inflow, is typically within one month for rainwater tanks, whereas this could be many years for a large reservoir. Therefore, demand predictions are not critical and can be disregarded. Current demand can be estimated with reasonable accuracy based on the household characteristics. Therefore, this condition could also be disregarded as it will be included in the simulation scenario.

3.5.3 Stream flow restoration

The occurrence of stream baseflow is dependent on complex relationships between catchment topography, soils, land use and climate (Price 2011). However, as catchment scale implications are precluded from the scope of research only the frequency of rainfall is considered in the occurrence of stream baseflow; therefore, monthly statistics should have this basis. The downstream requirements could be determined by defining pre-urban stream hydrology or ecological limits to hydrologic alteration that the stream ecosystem can withstand.

3.5.4 Rainfall forecasts

Finally, given the simplified hydrology of roof catchments, rainfall forecasts are more suitable than predictions of stream flow. Using rainfall forecasts as a control signal for residential rainwater tanks is certainly novel. However, data limitations could be problematic. The duration and quality of rainfall forecasts archives could be considerably less than rainfall observations. Further examination of data limits or methods to supplement insufficient data would be necessary to conduct a long-term simulation.

3.5.5 Summary of operating conditions

This limits relevant hydrologic conditions to current storage, predicted rainfall and downstream requirements. To incorporate the current storage, environmental flows could be limited to periods where storage is above a minimum level. Therefore, the basis of the operating rules is to establish this minimum water storage.

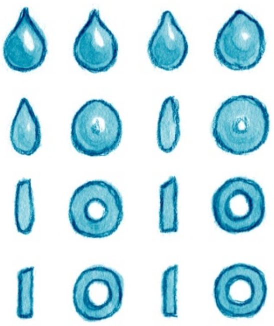
The leaking rainwater tank would have a fixed design incorporating a trickle release outlet at this storage level. Whereas adaptive tanks would have a flexible design where the minimum water storage varies, based on rainfall predictions. These predictions could be incorporated in two ways, either as short-term rainfall forecasts or as historical monthly statistics where seasonal rainfall exists.

The scope of establishing operating rules will therefore be limited to a fixed design for the leaking rainwater tank and a flexible design for the adaptive rainwater tank which is based on monthly rainfall statistics, daily rainfall forecasts or a combination of both.

Chapter 4 Modelling Rainwater Systems

The UrbanTank model was programmed in MathWorks MATLAB and is a mass-balance behavioural simulator for conventional, leaking and adaptive rainwater tanks. The principal aim is to estimate the dual-duty performance of rainwater tanks. Where possible parameters are based on independent research and results are validated by current simulation practices and independent field measurements.

The capacity of the model is expanded in subsequent chapters 5, 6 and 7 through detailed assessment of outdoor water use; measuring the environmental benefits of rainwater tanks; and supplementing rainfall forecast archives.



4.1 Introduction

There are two alternatives to derive rainwater harvesting performance. One is to monitor existing systems over a limited period and obtain empirical data which could potentially be highly accurate for a specific time, location, type of construction and water use behaviour. This type of research has been undertaken by many and one recent Australian example was 12 months monitoring of 52 rainwater tanks throughout Sydney (Ferguson 2012).

Unfortunately, the sole purpose of most rainwater tanks is to provide a water supply alternative which is problematic for examining or optimising their dual-duty performance. The alternative is to employ a behavioural model that performs a mass-balance simulation which is dependent on empirical data to calibrate model parameters and validate model output.

Simulation is the process of establishing a simplified model of a complex system and therefore results carry degrees of uncertainty. There are obvious advantages in the capacity to test endless scenarios, utilise historic rainfall data from virtually any location, and obtain long-term results (100 years) in just a few minutes. It is therefore not surprising that many behavioural models have been constructed for rainwater tanks, with nineteen independent models reviewed in Chapter 3.

However, as it was concluded in the literature review, none of the rainwater simulators in their current form have the capacity to measure dual-duty performance or to incorporate adaptive management of environmental flows in response to rainfall forecasts or historic rainfall statistics. Thus, it is inevitable that yet another rainwater simulator is constructed and this will be founded on the work of others. Establishing, calibrating and validating this simulator are the aims of this chapter. The simulator’s capacity is enhanced by further studies in subsequent chapters 5, 6 and 7, relating to water use, measuring environmental benefits and preparing rainfall forecast archives for long-term simulation.

Guidelines for simulating rainwater tanks suggest accuracy is dependent on the model artefacts of time-step; supply-spill sequence and catchment hydrology; and to a lesser extent, demand patterns and duration of climate data (Lucas *et al.* 2006; Mitchell 2007). This chapter will study each of these aspects to ensure the model construct and input data is suitable for performance estimates with limited uncertainty and high relevance. This chapter will also introduce new performance metrics to increase the comprehension of rainwater tanks.

4.2 A systems overview of rainwater harvesting

For the purposes of creating a rainwater tank simulator, the system may be deconstructed into four principal components: catchment; water store; water use; and, in the case of adaptive rainwater tanks, operating rules.

4.2.1 Rainwater catchment

The catchment is the subsystem of all water collection, treatment and conveyance components before the tank inlet and comprises a connected roof area, gutters, downpipes, and may also include leaf separators and first flush devices. For residential buildings, common roofing materials are tiles constructed from terracotta, concrete or slate; steel sheeting such as Colourbond ©, Zincalome © and galvanised iron; and, in the past, asbestos sheets were also used (White 2009). These non-porous surfaces are suitable for collecting rainwater as abstraction from wetting the catchment is minimal in comparison to green rooves or natural catchments.

Gutters are usually constructed from steel sheeting products and downpipes may also be PVC (White 2009). Most catchment materials are suitable for harvesting rainwater, however, lead flashing and zinc coatings used in Zincalome and galvanised iron can leach and cause contamination with known health risks (Schriewer *et al.* 2008; Kus *et al.* 2010).

The national average size of residential dwellings, measured by floor area, has been steadily increasing and is expected to approximate 250 m^2 in 2012 (Fig. 4-1). The average size of Queensland, New South Wales and Victorian homes is larger than other states with floor areas exceeding 260 m^2 in June 2009 (BoS 2010d). In Queensland, the June 2008 average size was 247.3 m^2 which is comparable to surveys at similar times from households which have adopted rainwater tanks (237 m^2) and those which have not (215 m^2) (White 2009).

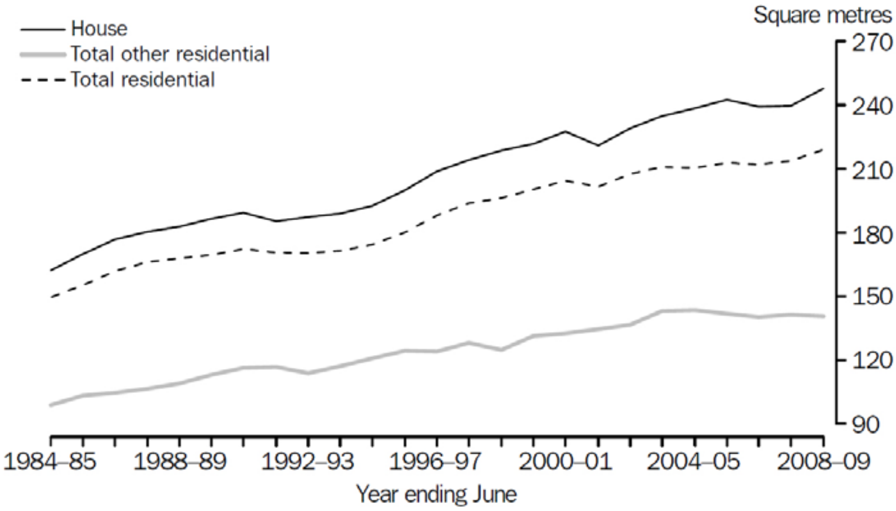


Fig. 4-1 Increasing trend of Australian house floor area. Source: (BoS 2010d)

White (2009) also reports the portion of roof area that is connected to rainwater tanks (64.4%) or could be practically connected if a tank was installed (80%). From this data, mean roof catchments are estimated at 150 m^2 to 170 m^2, which is greater than recent recommendations of 50% of available roof area or 100 m^2, whichever is the minimum (QDIP 2007a). Ferguson (2011) reports a higher average connected roof area of 210 m^2 from a sample of 52 Sydney houses.

Rainwater yield is highly sensitive to the connected roof area, as demonstrated in Chapter 3 and by others (MJA 2007a). In most cases, increases in connected roof area can significantly increase rainwater yield and system reliability. However, in subsequent chapters it is proposed to study the dual-duty performance of water supply and restoring aspects of pre-urban stream hydrology. Both of these objectives are competing for storage, which is finite in residential rainwater tanks. Therefore, an optimum connected roof area may exist for the dual-duty performance. To establish this, a range in roof areas will be studied as previously mentioned in Chapter 3.

4.2.2 Rainwater storage

The volume of rainwater tanks in urban areas is often limited by the available space. It is not common to see volumes greater than 10 kL or less than 2 kL. A recent survey of South East Queensland reports a minimum adopted volume of 2.5 kL and 5 kL being the most frequent (White 2009). This is similar to the mean sample reported in Sydney of 4.2 kL (Ferguson 2011). It is almost universal in Queensland to find this volume dedicated to water supply. There are few examples of trickle release chambers to enable environmental flow or mains trickle-top-up arrangements.

A mains trickle-top-up arrangement was found at 6% of Sydney houses (Ferguson 2011). This approach allows mains water to slowly top up the rainwater tank to a pre-set level, and commences when the water level drops below a lower threshold (Barry & Coombes 2008). This arrangement is proven to reduce the peak demand on water mains (Coombes *et al.* 2002; Lucas *et al.* 2009), which is a critical service factor and results in delaying upgrades to reticulation infrastructure. However, this is not without disadvantages to the household as tank water is pressurised before use and the household must pay these energy costs. Also, this arrangement limits capacity to capture and store rainwater. It is for these reasons that the trickle-top-up arrangement is not recommended and precluded from further assessment.

However, results are still relevant to rainwater tanks fitted with trickle-top-up systems but only the dedicated rainwater storage volume should be considered and not the total tank volume.

4.2.3 Rainwater demand

In most households, rainwater is fit for non-potable end use which can constitute up to 80% of total household water consumption. However, it is more common to restrict rainwater to outdoor use, toilet flushing and clothes washing machines. Opportunities exist to extend supply to hot and cold water for baths and showers and this could potentially increase the yield from rainwater systems and extend their role in urban water security strategies. However, there is some resistance to the idea of supplying water heaters as moderate temperatures may encourage bacterial growth (enhealth 2004). Rainwater demand scenarios will be established in this chapter that represent the typical urban residential settings.

4.2.4 Rainwater operating rules

Currently, most household rainwater tanks are low-technology and have limited capacity to respond to changes in their environment. The trickle-top-up arrangement is one exception and is an example of an operating rule that achieves secondary outcomes to the principal role of water supply. Another is from the Australian company Micromet that developed a system where rainwater is diverted from residential rainwater tanks via a centralised control system into stormwater mains. It is then harvested at a central point downstream for irrigating open space (Townsend 2012). This initiative has demonstrated opportunities exist to create adaptive integrated rainwater tanks that reduce municipal water demand while increasing the stormwater management outcomes of the catchment.

The trickle release arrangement is another simple operating rule where surplus stored water is slowly released from the rainwater tank to achieve many objectives. This dissertation will examine this leaking approach to manage water storage, and in addition, an adaptive approach where surplus stored rainwater is quantified using rainfall statistics or rainfall forecasts and then released as environmental flow to reduce tank overflow and restore pre-urban aspects of stream hydrology.

Therefore, the aim of this chapter is to establish a mass-balance behavioural model UrbanTank to simulate the dual-duty performance of various rainwater tank alternatives and operating procedures. Where possible model parameters will be calibrated by empirical data and model results will be verified with independent studies.

4.3 Model artefacts

4.3.1 Time-step

Greater computational resolution may be necessary to simulate processes occurring in one or more model components. The four components of catchment, water store, water use and operating rules, can operate at independent time-steps to improve computational efficiency. Rainfall records taken at fine intervals (pluviograph) are necessary to quantify overflow from gutters during bursts of high intensity rainfall. Therefore, the roof runoff model component will operate at the six minute time-step which is the finest time-step widely available for pluviograph data.

An appropriate model time-step must be adopted for the water storage component so that accurate simulation is achieved. If the time-step is too large, then significant errors may be introduced through averaged values. Adopting a monthly time-step could fail to simulate excessive tank overflow from large daily rainfall. Similarly, adopting a daily time-step could fail to simulate peak household water use, which may reduce overflow. However, if the time-step is too small, then additional computation could be unwarranted if results are barely improved.

Fewkes (2000a) reports modelling time-step constraints for volumetric simulation of reservoirs, based on a storage fraction, $V_t/(A \times P)$, where V_t is the total storage capacity (kL), A is the roof area (m^2) and P is the annual precipitation (m). For small storage fractions (below or equal to 0.01) an hourly time-step is recommended; for medium storage fractions (0.01to 0.125) a daily time-step is recommended; and monthly is recommended otherwise. Mitchell (2007) is in agreement by reporting a daily time-step may significantly underestimate rainwater yield in small storages as the diminished buffer capacity cannot be accurately modelled.

A relationship between storage size, model time-step and model accuracy was reported by Knights and Wong (2008). In this Sydney study, rainwater storage from 0.2 to 10 kL was simulated using a six minute and daily time-step for the roof runoff and household water use components. Reduced accuracy is reported for a daily time-step where the storage volume is 1.5 kL or less. This scenario equates to a storage fraction of 0.008 or less, where the roof area is 180 m^2 and average annual rainfall is 1100 mm, as reported. Therefore, these results are consistent with Fewkes (2000a) and Mitchell (2007), so far as the errors that are expected from using a daily time-step with small storage fractions. Furthermore, Coombes and Barry (2007) report similar underestimations of rainwater yield when using daily time-step and conclude by recommending a six minute time-step.

Also, Baek (2011) confirms these results by simulating the supply reliability from moderately sized agricultural reservoir (storage fraction of 0.22) in Western Australia. Results demonstrated there is a risk of underestimating reliability with an annual time-step and overestimating with a daily or weekly time-step but the monthly time-step was reasonably accurate. A finer time-step could introduce excessive computation and increase the simulation sensitivity to model parameters.

A sub-hourly time-step is frequently used to simulate rainwater tanks (Coombes & Barry 2007; Knights & Wong 2008) which is beyond the scope investigated in the storage fraction (Fewkes 2000a). Therefore, further investigation may be necessary with storage fractions much less than 0.01. In the proposed research, some scenarios will have a small storage fraction, such as 0.006 (2.5 kL tank, 200 m^2 roof and 2000 mm annual rainfall, in Darwin). As this fraction is marginally less than 0.01, an hourly time-step will be adopted for simulation of the rainwater storage. This time-step is consistent with other studies on water storage simulation (Fewkes 2000b; Villarreal & Dixon 2005; Brodie 2008; Khastagir 2008; Mitchell *et al.* 2008a; Basinger *et al.* 2010).

Also, the time-step for the household water use component of the model must be considered. As the proposed research has a basis of hypothetical simulation of scenarios that represent typical urban residential settings, the time-step is governed by data availability. Many models for urban water demand are based on an hourly time-step to quantify peak demand (Aly & Wanakule 2004; Ghiassi *et al.* 2008; Herrera *et al.* 2010). Furthermore, a common method for reporting surveyed household demand is by hourly diurnal plots (Roberts 2005; Coombes 2006b; Adamowski 2008; Lucas & Coombes 2009b; Lucas *et al.* 2009; Thyer *et al.* 2009; Willis *et al.* 2011b). Therefore, it would be prudent to utilise this research and adopt an hourly time-step for the household demand component.

However, results from the parameter sensitivity analysis in Chapter 3 showed rainwater yield was insensitive to the presence of an hourly diurnal pattern which is consistent with other independent studies (Mitchell *et al.* 2008b). This can be explained by the storage fraction of the base scenario (0.07) and the recommendations by Fewkes (2000a) to use a daily time-step. With the diurnal pattern, an hourly time-step was applied which introduced excessive computation with little or no improvement in simulation results. However, as previously stated, other scenarios have smaller storage fractions. Therefore, the diurnal pattern is applied universally as it did not increase model error.

Finally, the frequency of altering operating conditions needs to be considered. As these conditions are based on quantifying surplus stored water from monthly rainfall statistics or daily rainfall forecasts, the finer (daily) time-step will be adopted.

In summary, the model will simulate roof runoff at six minute intervals to quantify gutter overflow and incorporate rainfall intensities within pluviograph observations; then aggregated into hourly inflows which will be combined with hourly water use estimates to calculate the hourly water balance of yield, overflow, and environmental flow; and finally, surplus stored water is estimated on a daily basis and if necessary, environmental flows are enabled over the next 24 hours (Fig. 4-2).

Roof evaporation and first flush diversion is deducted from six minute intervals of rainfall and roof runoff, respectively, until the accumulated abstractions equals daily depths of 0.4 mm each.

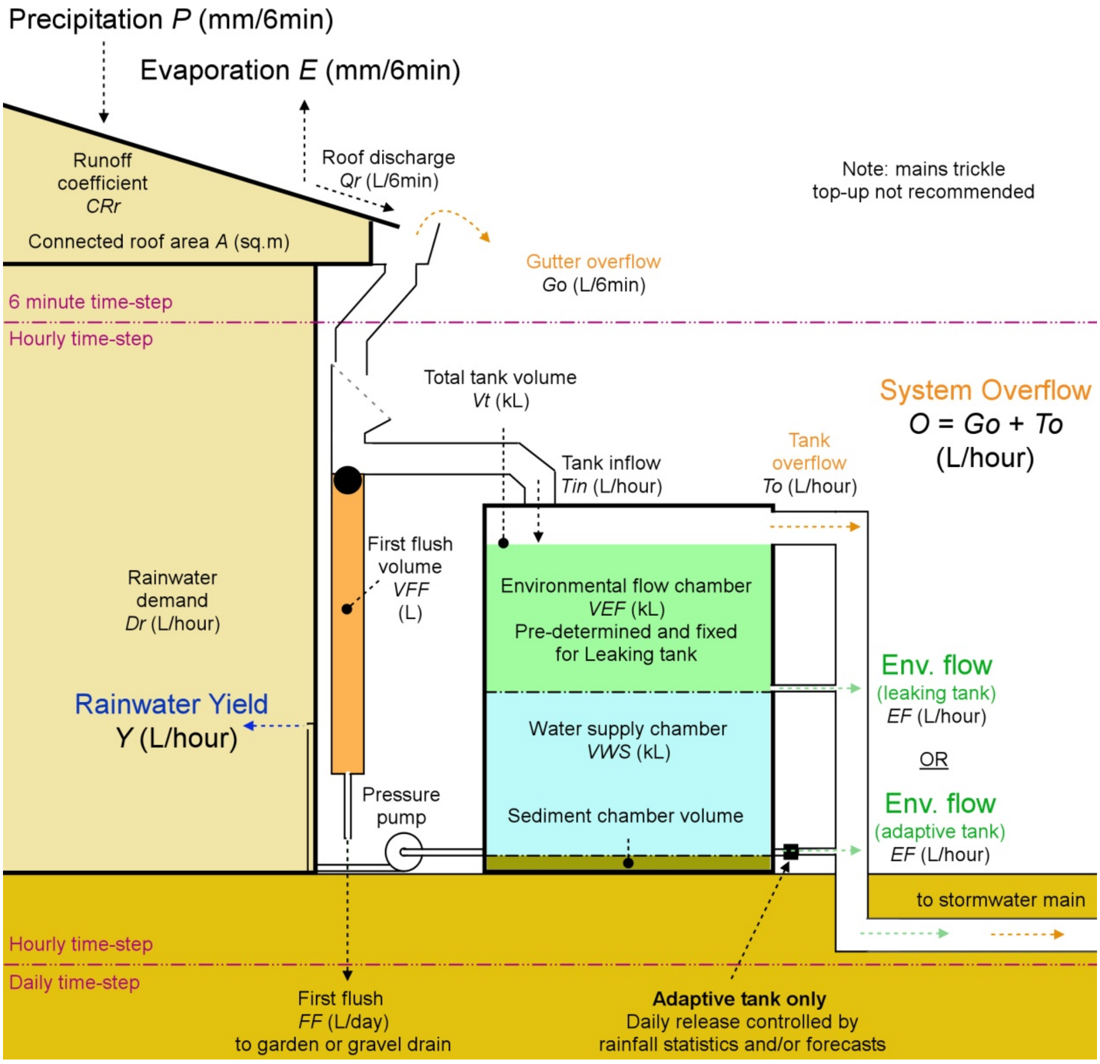


Fig. 4-2 Rainwater simulation model with environmental flow alternatives

4.3.2 Spill-supply sequence

The model artefact of spill-supply sequence is important to ensure a conservative performance estimate of yield and overflow is obtained. The spill-before-yield sequence (Fig. 4-3) is discussed by many (Liaw & Tsai 2004; Villarreal & Dixon 2005; Jenkins 2007; Mitchell 2007). The sequence is followed each time-step to calculate the water fluxes of rainfall-runoff losses, first flush, overflow, environmental flow and rainwater yield from rainfall input data and water use estimates. With this approach overflow is overestimated due to being early in the sequence, and yield is underestimated due to being the final water flux. This is ideal for the dual objectives of maximising yield while managing overflow. The magnitude of error induced by the model sequence is positively correlated to the model time-step (Mitchell 2007). As an hourly time-step is employed by the water storage component, these errors are minor and should provide a conservative performance estimate.

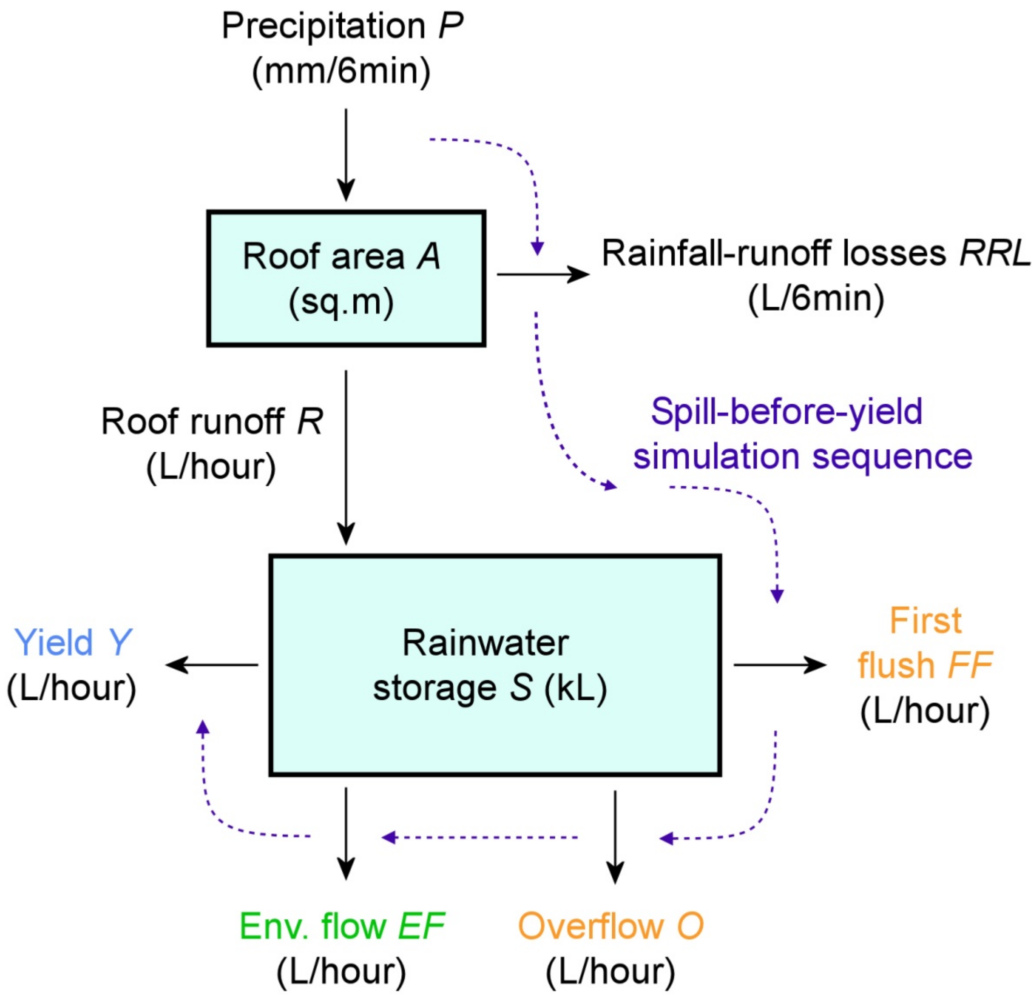


Fig. 4-3 Spill-before-yield sequence of rainwater harvesting simulation

The estimated stored rainwater S_n (kL) at the start of each time-step is calculated with (4-1) where: S_{n-1} is the stored rainwater from the previous time-step (kL) and water fluxes are as shown (Fig. 4-3, converted to kL) and derived from the discussion following.

$$S_n = S_{n-1} + R - FF - O - EF - Y \qquad \textbf{(4-1)}$$

4.3.3 Rainfall input data

Precipitation input data P (mm/6min) consisted of historic pluviograph observations taken at six minute intervals from a single weather station in each capital city. This data is available by request from the Australian Bureau of Meteorology (BoM) website (BoM 2012d). BoM has compiled a list of reference climate stations, specifically for long-term assessment where high quality data is desired. However, this list was formed for climate change analysis and the selection criteria excluded stations in large urban areas (BoM 2012a). Therefore, a review of the metadata from stations in and surrounding capital cities was necessary to locate the most suitable data. Stations were chosen on the basis of their proximity to capital cities, the duration of records, the most recent period of records, and the completeness of observations. Adopted stations and summary data are shown (Table 4-1).

Significant periods of missing data were discovered during quality checks. In some cases continuous periods exceeded 300 days. Where possible years with poor completeness were avoided (Fig. 4-4), particularly if there was a notable reduction in rainfall observed for that year. Unfortunately, this approach could not be consistently applied as simulation periods would have been significantly reduced in some locations. It is widely recommended that long simulation periods (20 years or greater) are adopted for accurate simulation of water storages (Liaw & Tsai 2004; Boughton 2007; Mitchell *et al.* 2008b).

Table 4-1 Pluviograph stations adopted for analysis in capital cities

Station	Description	District	Opened	Status	Records[a]
023090	Kent Town	Adelaide Plains	1977	open	94.1%
040913	Brisbane	Moreton South Coast	1999	open	87.0%
070014	Canberra airport comparison	Sthn Tablelands Gburn-Monaro	1939	closed	85.5%
014015	Darwin airport	Darwin-Daly	1941	open	91.5%
094029	Hobart (Ellerslie Rd)	Southeast	1882	open	92.1%
086282	Melbourne airport	East Central	1970	open	88.9%
009021	Perth airport	Central Coast	1944	open	92.6%
066062	Sydney (observation Hill)	Metropolitan (E)	1858	open	93.9%

[a] Pluviograph records were obtained on 18/11/2011 and the date of the final observation varied by location. The completeness of records is calculated for the

complete archive, which in some stations did not commence during the opening year listed.

The 31 year simulation period for Adelaide is from 1978 to 2008 with 97.3% of observations recorded. Over this time, a low mean annual rainfall with a small variation was observed (518 mm/y ± 122 mm/y). No trend in annual rainfall is apparent for this short period. Therefore, this data shall provide a strong representation of the long-term average conditions in Adelaide.

In Brisbane, limited data was available at the primary weather station and no additional stations could be located to suitably supplement the pluviograph observations. The 8 year simulation period is from 2001 to 2008 with 99.9% of observations recoded. Over this brief period, annual rainfall is moderate and varies moderately (874 mm/y ± 243 mm/y). The long-term annual average rainfall for Brisbane is 1090 mm, calculated from daily observations at Toowong Bowls Club (station 040245) for the non-continuous period 1890 to 2012. The adopted pluviograph data has notably less rainfall (80%) and this is expected to produce yield estimates that are below the long-term average. Therefore, this data should provide a conservative estimate in Brisbane.

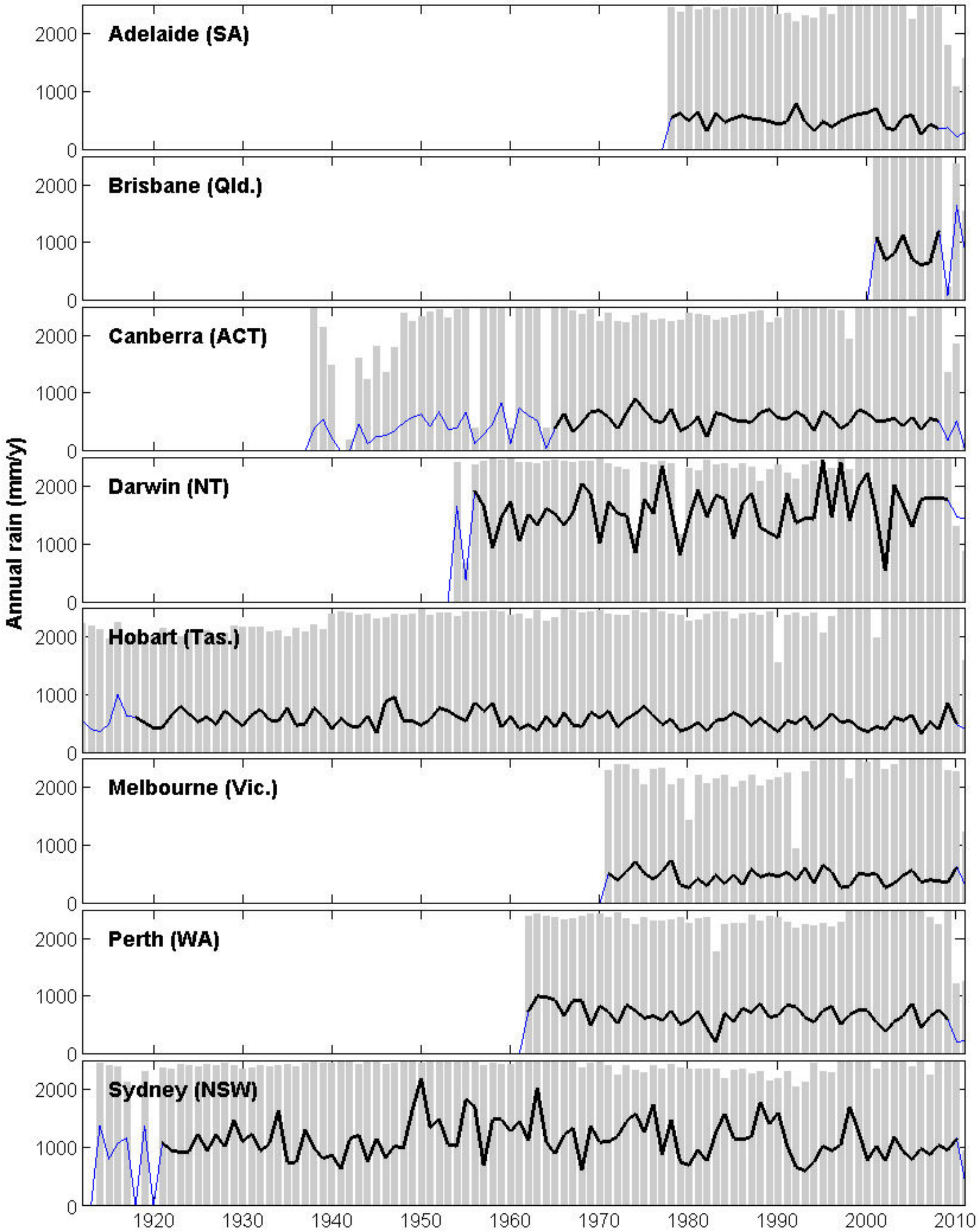


Fig. 4-4 Annual rainfall from accumulated pluviograph observations in Australian capital cities (**blue**), completeness of annual records (**grey bars**) and adopted input data (**black**).

In Canberra, significant periods of missing data around 1960 reduced the simulation period to 44 years from 1965 to 2009. Over this period, 95.7% of observations were recorded with a low mean annual rainfall and a small variation (559 mm/y ± 135 mm/y). Missing records are evident in 1998 however this data was included as the annual rainfall is within the standard deviation. No apparent long-term trend is evident in annual rainfall. Therefore, this data should provide a strong representation of the long-term average conditions in Canberra.

In Darwin, significant periods of missing data were throughout the pluviograph records. A simulation period of 54 years from 1956 to 2009 is adopted. Over this period, 94.2% of observations were available and a high annual rainfall and high variation was reported (1583 mm/y ± 393 mm/y). Unfortunately during the 1970s, missing observations resulted in underestimated annual rainfall. Given the high variability of rainfall in Darwin, the annual rainfall in the 1970s is characteristic of this site and the records were included in the simulation. The long-term trend in annual rainfall suggests a slight increase is occurring. Therefore, this data should provide a reasonable representation of long-term average conditions and possibly a slightly conservative estimate of future rainwater yield in Darwin.

In Hobart, the completeness of records was high with 92.6% of observations recorded during the 93 year simulation period from 1918 to 2010. Suitable pluviograph data was available from 1912 however temperature data used in the outdoor water use model in Chapter 5 limited the simulation period. Over this period, a low mean annual rainfall with a small variation was observed (578 mm/y ± 143 mm/y). These long-term records demonstrate annual rainfall is not trending upwards or downwards. Therefore, this data should provide a strong representation of long-term average conditions in Hobart.

In Melbourne, significant periods of missing data are throughout the pluviograph records. A simulation period of 40 years from 1971 to 2010 is adopted. Over this period, 89.9% of observations were available and a low annual rainfall with a small variation was recorded (467 mm/y ± 124 mm/y). Record completeness is poor in 1992 but as the annual rainfall is within the standard deviation the data was included. There is no apparent long-term trend in annual rainfall and this data should provide a good representation of long-term average conditions in Melbourne. It should be noted that rainfall in and around Melbourne can vary significantly and this will affect the relevance of results.

In Perth, the completeness of records was high with 94.3% of observations available during the 48 year simulation period from 1963 to 2009. Over this period, a low annual rainfall with small variation is observed (694 mm/y ± 164 mm/y). Records were poor in 1983 but excluding this data would significantly reduce the simulation period. The long-term trend indicates a slight reduction in annual rainfall is occurring. Therefore, this data should provide a reasonable representation of long-term average conditions and perhaps a slight overestimate of future rainwater yield in Perth.

Finally, in Sydney, completeness of records is high with 96.5% of observations available for the 90 year simulation period from 1921 to 2010. Over this period, a high annual rainfall with significant variation is reported (1147 mm/y ± 331 mm/y). There is no apparent long-term trend that annual rainfall is increasing or decreasing but starting from 1950, there is a notable wet to dry oscillation with a frequency of 10 to 13 years. Often, dry years can be observed 5 to 7 years after peaks. This trend is continuing with 2011 another year of high rainfall. Therefore, the long-term average conditions may be less meaningful than upper and lower percentiles of rainwater yield. The duration of this data will assist to quantify these characteristics of rainwater harvesting in Sydney.

4.3.4 Roof hydrology

As discussed in the literature review, a simplified runoff model based on the Rational Method (IEAust 2001) is commonly used to estimate discharge from rooves constructed of materials with low porosity. Following the review of roof runoff parameters in Chapter 2, a fixed runoff coefficient CR_r of 0.9 and depth of initial loss D_{il} of 0.4 mm was adopted, as reported by Chapman and Salmon (1996).

4.3.5 Gutter overflow

From the empirical data discovered in the literature review, the combined roof runoff from all connected gutters and downpipes R (L/6min) is determined with (4-2) where, N_{dp} is the number of connected downpipes and Q_r (L/6min) is roof discharge, as defined in Section 2.7.

$$R = \begin{cases} 0.9 \times G_{hc} \times N_{dp}, & 0.9 \times G_{hc} \times N_{dp} < Q_r \\ Q_r, & \text{otherwise} \end{cases} \quad \textbf{(4-2)}$$

Also, gutter overflow O_g (L/6min) is determined with **(4-3)**.

$$O_g = \begin{cases} Q_r - R, & R < Q_r \\ 0, & \text{otherwise} \end{cases} \tag{4-3}$$

4.3.6 First flush devices

Based on the results of the literature review, a D_{ff} of 0.4 mm/d or 40 L / 100 m^2 / d was adopted for the proposed research. Therefore, the daily first flush abstraction FF (kL) is determined with (4-4) where R_d is the accumulated daily roof runoff (kL).

$$FF = \begin{cases} R, & \sum R \leq D_{ff} \times A \\ D_{ff} \times A, & \text{otherwise} \end{cases} \tag{4-4}$$

Finally, the tank inflow T_{in} (L/hour) is determined with **(4-5)**.

$$T_{in} = R - FF \tag{4-5}$$

4.3.7 Connected roof area

The connected roof plan area A (m^2) is varied through simulation scenarios which represent a variety of urban dwelling setting. As previously stated in Section 4.2.1, the mean connected roof area for urban dwellings is 150 m^2, with most systems likely to be within the range of 100 to 200 m^2.

4.3.8 Household water consumption components

From the literature review, the current annual average household water demand D_t is approximately 200 kL for most states and territories but can range from 130 kL up to 300 kL. Further exceptions include the Northern Territory and Tasmania, where higher state estimates are 450 and 350 kL, respectively, but could not be verified by independent research. As rainwater is supplied to limited end uses, the split between various end uses must be examined.

The main distinction between the components of household water consumption is whether water use occurs inside or outside. The outside or external component is similar to the variable or seasonal component and likewise the internal component is mostly insensitive to weather. In this research the daily internal water demand is presumed to be constant and approximately 80% of D_t. This is consistent with current trends of reducing demand by limiting outdoor water use (Fig. 4-5).

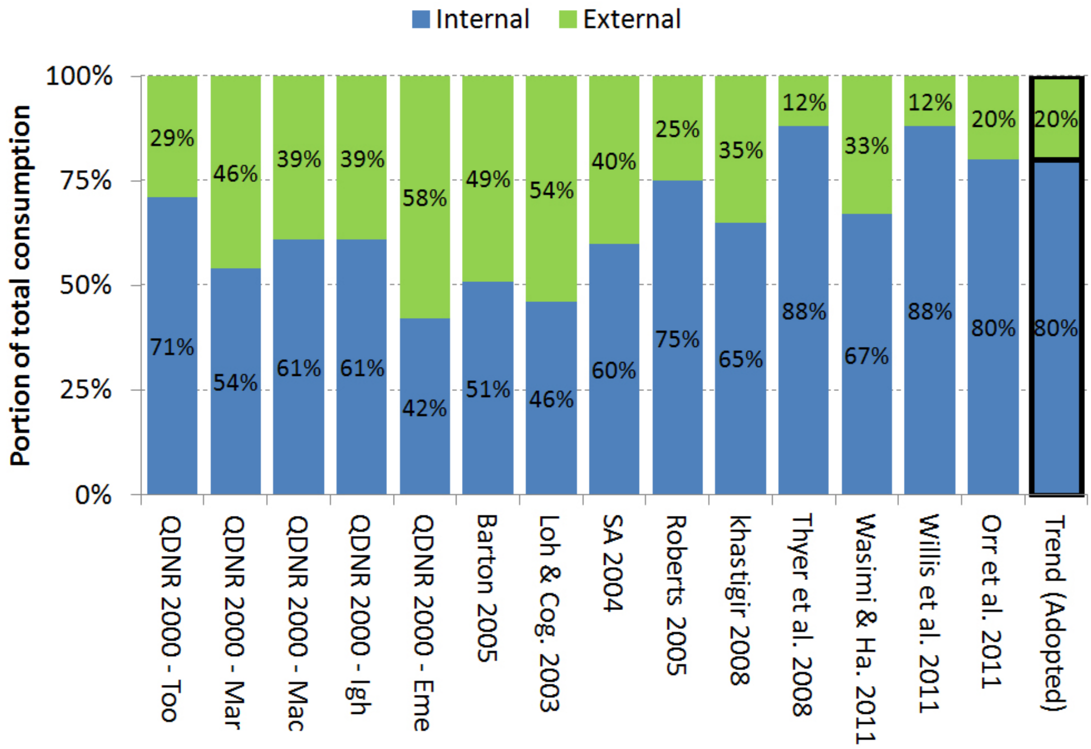


Fig. 4-5 Household consumption internal external split (2000 to 2011) Toowoomba (**Too**), Maroochydore (**Mar**), Mackay (**Mac**), Ingham (**Igh**) and Emerald (**Eme**)

Within the home, water use splits are commonly reported between the bathroom, laundry, kitchen, toilet and other areas. The portions of consumption for the average household are reported to be reasonably consistent in spatial and temporal aspects (Fig. 4-6). Therefore, the average of these studies is adopted for the internal splits in this research. It should be noted that the component splits of household water consumption within a survey sample can vary significantly depending on the household characteristics (Fig. 4-7). The most varied component is external water use and can range from zero to approximately 70%, when individual households are considered.

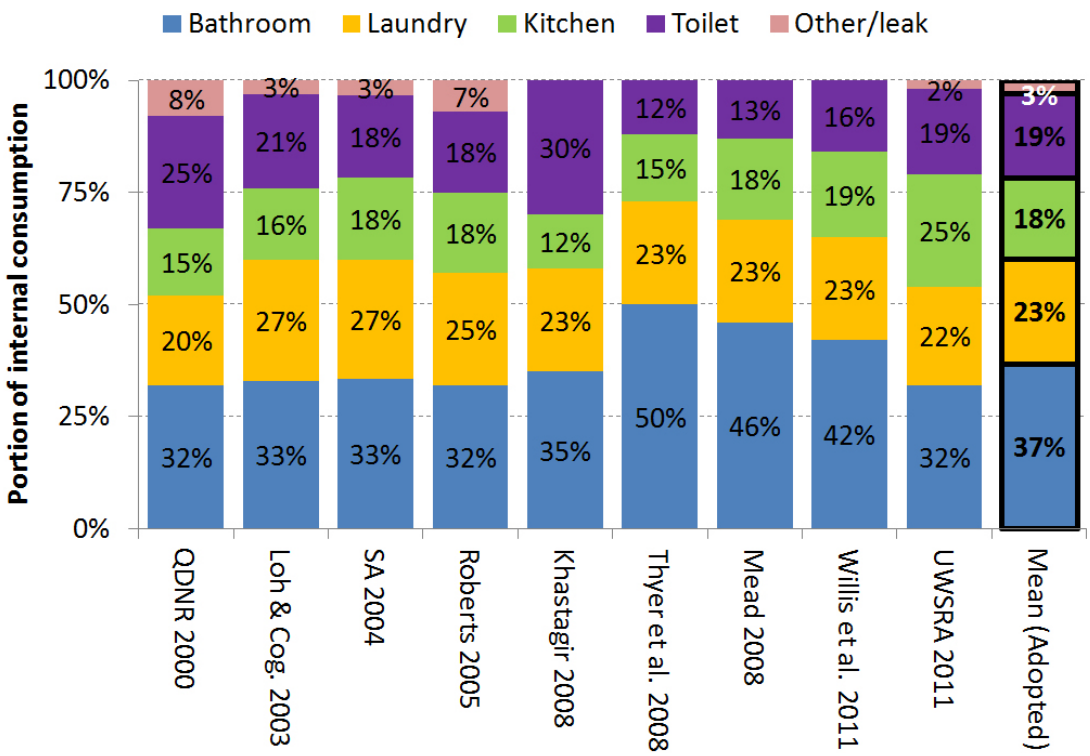


Fig. 4-6 Household consumption internal components (2000 to 2011)

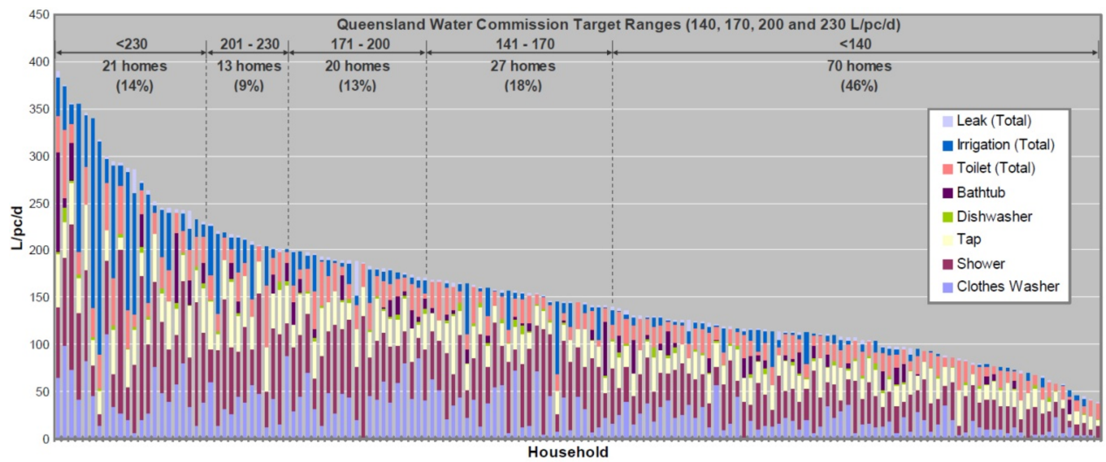


Fig. 4-7 Distribution of household daily per capita consumption by activity breakdown. Adapted from (Willis 2010)

4.3.9 Household rainwater demand scenarios

Rainwater is typically suitable for all non-potable end uses, which can be as much as 80% of total household consumption. However, there are few examples in urban Australia where this arrangement occurs. It is typical for rainwater to be supplied to toilets, cold laundry taps, one external tap and possibly to cold and hot water for showers and baths (enhealth 2004; QDIP 2007a; BASIX 2010). Rainwater demand scenarios were established (Table 4-2) based on the following observations and assumptions: (1) D_t is typically 200 kL but can vary from 130 up to 300 kL; (2) equal portions of hot and cold water are assumed to be supplied to the bathroom but only cold water is from rainwater tanks; (3) half the external water use is assumed from the rainwater tank and external water use is trending towards 20% of D_t; and (4) estimates of consumption from the laundry (or clotheswashing machine) is assumed to be entirely cold water and supplied from the rainwater tank.

Table 4-2 Adopted annual rainwater demand scenarios

Scenario	**Total D_t**	**Ext. 20%**	**Toilet 15.2%**	**L'dry 18.4%**	**Bath 29.6%**	**Other 16.8%**	**R'water Dmd D_r**
Low	130 kL	-	20 kL	24 kL	-	-	**44 kL**
		(0%)	(15.2%)	(18.4%)	(0%)	(0%)	(33.8%)
Med.	200 kL	20 kL	30 kL	37 kL	-	-	**87 kL**
		(10%)	(15.2%)	(18.4%)	(0%)	(0%)	(43.5%)
High	300 kL	30 kL	46 kL	55 kL	46 kL	-	**176 kL**
		(10%)	(15.2%)	(18.4%)	(14.6%)	(0%)	(58.7%)

Note that parentheses include portions of D_t intended to be supplied by rainwater.

4.3.10 Diurnal water use patterns

In keeping with earlier conclusions of an hourly time-step for the demand component of the rainwater simulation model, diurnal water use patterns were examined for Upper Parramatta (Coombes *et al.* 2001); Newcastle (Coombes 2002); Perth (Loh & Coghlan 2003); the Yarra Valley (Roberts 2005); Newcastle, Brisbane and Gosford (Hauber-Davidson & Idris 2006) sighted in (Lucas *et al.* 2009); Hornsby Heights (Lucas & Coombes 2009b); Hervey Bay (Turner *et al.* 2010) and the Gold Coast (Willis 2010). Of these studies only three attempt to differentiate internal and external diurnal patterns, which is necessary to apply seasonal variability only to the outdoor water use component.

Internal and external diurnal water use was normalised for Perth (Loh & Coghlan 2003), the Yarra Valley (Roberts 2005) and the Gold Coast (Willis 2010) to facilitate a comparative assessment. The results demonstrate these studies are highly consistent (Fig. 4-8). The adopted diurnal patters for internal and external water use components was derived from the distribution means (Fig. 4-8 and Fig. 4-9) and combined to give the final composite diurnal pattern (Fig. 4-10).

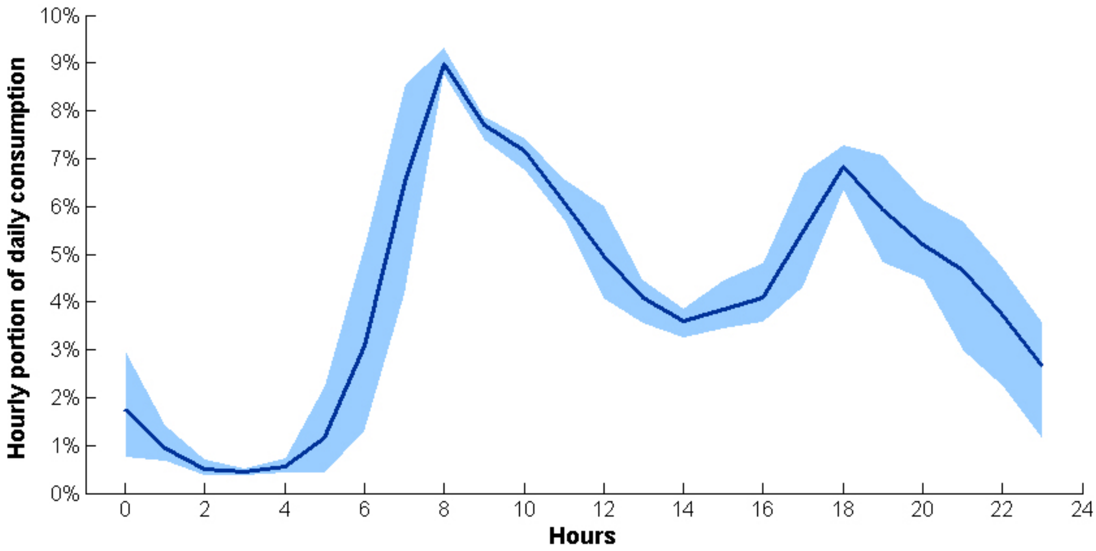


Fig. 4-8 Internal diurnal water use distribution (**light blue**) and distribution mean as adopted pattern (**dark blue**)

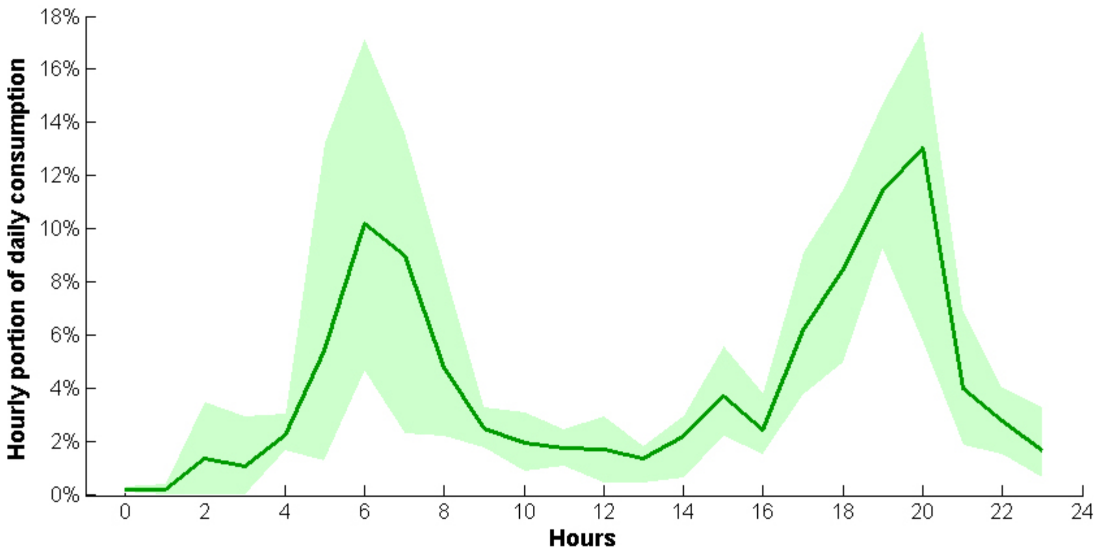


Fig. 4-9 Outdoor diurnal water use distribution (**light green**) and distribution mean as adopted pattern (**dark green**)

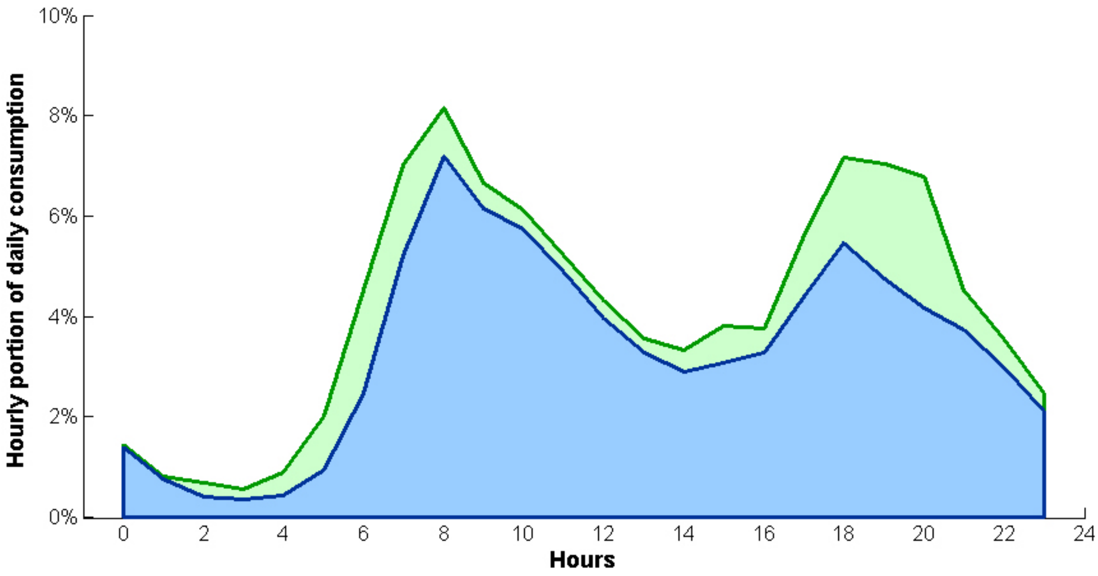


Fig. 4-10 Adopted composite diurnal pattern with 80% internal or non-seasonal demand (**blue**) and 20% outdoor or seasonal demand (**green**)

Common to all internal diurnal patterns are peaks at 8 am and 9 pm and troughs in the early morning and early afternoon, which is typical of water use behaviour on working days. Internal water use on weekends is more atypical and difficult to predict so the working-day pattern was applied universally.

Outdoor water use peaks and troughs are similar to the internal pattern but more variation was discovered across the results in the literature. Peaks are approximately two hours earlier in the morning and later in the afternoon which is consistent with activities around the working family. Also, outdoor water use at midday is a lower portion of total water use than for the internal pattern. Again, weekend patterns of outdoor water use are atypical and the working-day pattern was applied universally.

Outdoor water use is further modified to account for the seasonal nature of this component. This is achieved by applying a daily demand coefficient, which is derived from daily rainfall and temperature indices, as discussed in Chapter 5.

The final composite diurnal pattern demonstrates up to 8% of total daily water use can occur in one hour at approximately 8 am. The majority of which could be potentially sourced from the rainwater tank. This demonstrates rainwater tanks can reduce peak hour water demands on municipal mains, while supply is available.

4.4 New performance metrics

In the literature review the adopted metrics for measuring the performance of rainwater systems were examined and it was recommended that an alternative is introduced for supply reliability. Also, the environmental benefit index should be adapted for the research context and these metrics could combine to provide a measure of overall dual-duty performance. Additionally, it would be useful to compare the duration of the maximum continuous period with and without environmental flow and rainwater supply for the various rainwater tanks being studied.

4.4.1 Supply independence

Supply independence SI is introduced as an alternative to supply reliability, as the latter promotes reliably supplying rainwater to a limited number of uses, rather than simply encouraging consumption of rainwater. SI is the principal metric for determining capacity to mitigate household reticulated water demand. SI (unitless) is the ratio of average annual rainwater yield Y (kL) to average annual total household demand D_t (kL), rather than only rainwater demand as applied in other reliability metrics discussed in Chapter 2. SI is determined with (4-6).

$$SI = {}^{Y}/_{D_t} \tag{4-6}$$

This approach encourages supplementing reticulated water supply with rainwater for end uses that are fit for purpose. Therefore, striving to increase supply independence should increase rainwater yield and reduce the household reticulated water use. A household that is self-sufficient for water supply would have a supply independence of one but as rainwater is not usually suitable for potable use, self-sufficiency is unlikely and not recommended without appropriate treatment measures and routine maintenance.

4.4.2 Simplified environmental benefit index

Chapter 6 describes the simplifications made to the environmental benefit index EBI introduced by Walsh *et al.*(2010). EBI is the principal method to determine the restoration of stream hydrology of rainwater tanks. A value of one indicates full restoration and lower values indicate lower restoration. EBI is used in conjunction with SI to determine the dual-duty performance.

4.4.3 Volumetric utility

The dual-duty performance of providing a water supply and restoring pre-urban stream hydrology can be measured by the mean of SI and EBI. A weighted mean can be introduced where there is greater priority to achieve one duty over the other. In this case the sum of weights $(W_{SI} + W_{EB})$ would be one but for the studies herein, equal priority is adopted, i.e. $(W_{SI} = W_{EB} = 0.5)$. The volumetric utility metric VU (unitless) is determined with (4-7).

$$VU = w_{SI} \times SI + w_{EB} \times EBI \tag{4-7}$$

4.4.4 Environmental flow drought

While the EBI offers a comprehensive assessment of restoring pre-urban stream hydrology, it may be prudent to also consider the maximum continuous period within a given year were water storage is limited and environmental flows are not enabled. Given the various approaches for discharging environmental flows from the proposed systems, it is possible that the EBI may be similar while the sustained period without environmental flow may vary. This additional information will assist in recommending alternate types of rainwater tanks.

4.4.5 Environmental flow longevity

Similar to environmental flow drought, the longevity is the maximum period each year where environmental flows are continuously released. Likewise, this duration is expected to vary for the proposed rainwater storage arrangements and operating conditions.

4.4.6 Supply drought and longevity

Likewise, it may be useful for the rainwater supply drought and longevity to be determined following the methods outlined for environmental flow.

4.4.7 Household import water

Rainwater supplies will not always meet demand and the shortfall will be taken from imported water which is usually from the reticulated water mains. Mains water will also be supplied to all non-rainwater end uses in the household. Therefore, average annual imported water IW (kL) will be all non-rainwater consumed by the household and is a measure of household dependence on reticulated water supplies. IW can is determined with (4-8).

$$IW = D_t - Y \quad \textbf{(4-8)}$$

4.4.8 Household harvest

It may be useful to compare the total production or average annual harvest H (kL) from the various rainwater tanks. The harvest will include water consumed by the household and released as environmental flows and is determined with (4-9).

$$H = Y + EF \quad \textbf{(4-9)}$$

4.5 Operating rules for adaptive rainwater tanks

From the outcomes of Chapter 3, it was recommended to study rainfall observations and short-term forecasts to establish control signals for adaptive rainwater tanks. Three operating rules are examined which have the basis of actively managing the environmental flow chamber volume based on monthly rainfall statistics alone, the short-term rainfall forecast alone and responding to the signals collectively. Where a response to rainfall statistics is applied, environmental flow will generally occur after rainfall as is the case naturally. Responding to rainfall forecasts provides an avenue to commence environmental flow before rainfall occurs, whereas responding to the signals collectively should extend the duration that environmental flows are created.

Environmental flow rates will remain theoretically fixed, but could vary by location to represent larger baseflow that occurs in locations with rain dominant periods.

4.5.1 Rainfall statistics as a control signal

Average annual or seasonal trends of rainfall is generally a poor indicator of rainwater harvesting performance (Taylor 2010) as a large rain event can overwhelm storage and cause bias in these statistics. Thus, an alternative is discussed in Chapter 9 based on statistical representation of the three modes of failure of a rainwater tanks: *empty*, resulting from extended period of low or no rainfall; *sudden overflow*, resulting from a single extreme daily rain event; and *continued overflow*; resulting from less severe events that may be near continuous. The premise here is more on the occurrence of rainfall rather than the magnitude but both are essential.

A similar phenomenon could potentially define stream baseflow in small scale pre-urban catchments. A large rain event of a short duration would contribute less to stream baseflow than if the rainfall was distributed over a longer duration, due to the former generating excessive surface runoff. Also, baseflow is generally greater during periods of frequent rainfall and due to recession may cease altogether during extended dry periods (Boughton & Chiew 2003). It is desirable for rainwater tanks to mimic this behaviour to increase restoration of stream hydrology. A monthly or seasonal approach could potentially provide a gradual system change between wet and dry extremes. Thus, it is presumed the occurrence of baseflow correlates with the frequency of days per month were rainfall is above the abstractions from saturating vegetation and topsoil. Thus, the volume of the environmental flow chamber should be positively correlated to rainfall frequency.

4.5.2 Rainfall forecasts as a control signal

With rainfall forecasts, the volume of the environmental flow chamber would be positively correlated to the severity of the forecasts. This approach is less favourable for emulating the natural occurrence of baseflow but could limit the impacts of environmental flows on rainwater yield, by potentially restricting flows to times when tank overflow is most likely.

4.5.3 Combining rainfall statistics and forecast control signals

The basis of the combined approach is to extend the duration of environmental flow from the rainwater tank by potentially releasing flow before the storm commences, during the storm and afterwards.

4.6 Model verification

Independent estimates of average annual rainwater yield from conventional rainwater tanks were reviewed for testing model results. Complete details of the conditions, parameters and input data were not available for the independent assessments and therefore a precise agreement with simulation estimates is not sought. Where possible model parameters match the base scenario as described in the yield sensitivity analysis of Section 3.3.

Coombes and Barry (2007) estimate the long term average annual rainwater yield in Australian cities using the PURRS model. In the scenarios examined the connected roof area was 150 m^2, tank volume was 5 kL and annual average rainwater demand ranged by location (Table 4-3). Unfortunately in some scenarios different rainfall stations were adopted and this is evident in the results (Table 4-3).

Table 4-3 Model verification with PURRS simulation

Site	Rainwater demand D_r (kL)	PURRS yield (kL)	UrbanTank yield (kL)	% Difference	Compatible gauge
Adelaide	230	73	65	-11%	No
Brisbane	208	90	72	-20%	No
Darwin	482	121	122	1%	Yes
Hobart	175	60	58	-3%	Yes
Melbourne	197	77	49	-36%	No
Perth	350	98	82	-16%	No
Sydney	292	103	96	-7%	Yes

In scenarios with compatible rainfall stations, there are minimal discrepancies in rainwater yield (-7% to +1%). In all other scenarios estimates from UrbanTank were consistently lower than PURRS, with the largest anomaly in Melbourne (-36%). As previously mentioned Melbourne's rainfall is known to vary notably at a suburban scale. Rainfall at the station adopted in this research was 28% less than used with PURRS which explains the yield discrepancy.

It should be noted that high rainwater demands were adopted in the study by Coombes and Barry (2007) which are similar to the upper range of scenarios established in Section 4.3.9. These results demonstrate the model estimates are consistent with current modelling practices over a limited range of scenarios tested and where discrepancies occur, yield estimates from UrbanTank are conservative.

Additionally, simulated results were compared to independent desktop assessment in South-East Queensland (UWSRA 2011a; Beal *et al.* 2012) and field monitoring in Sydney (Ferguson 2011). Assessment in South-East Queensland employed four methodologies to examine the mains water savings of internally plumbed rainwater tanks installed in accordance with the recently abolished Queensland mandate. Estimated annual household water savings for the Redland local government area ranged by methodologies of mean value statistical analysis (33 kL), median value statistical analysis (41 kL), end use data analysis (43 kL) and simulation with the rainwater TANK model (46 kL). It should be noted that the TANK model incorporated a mains top-up arrangement and no attempt was made to remove the top-up volume from these yield estimates which introduce bias. Therefore, the TANK model analysis will not be considered further.

A simulation scenario was established using parameter values consistent with the Redlands assessment. Parameters include annual rainwater demand of 46 kL, a connected roof area of 100 m^2, tank volume of 5 kL that was initially empty, annual rainfall of 1348 mm (2008), and all other parameters as described in the base scenario of the yield sensitivity analysis in Chapter 3. The result was a rainwater yield of 36 kL which is consistent with the average of the analyses of households in the Redlands district (39 kL). Thus, the model results are verified by adopted practices for estimating rainwater yield in South-East Queensland.

Ferguson (2011) monitors 52 rainwater tank installations in Sydney for 12 months with an average annual household rainwater yield of 38 kL. Unfortunately, yield measurements from a specific system were not published and only average estimates were available, which is problematic for replicating results and validating model estimates. A simulation scenario was established based on the average of parameter values found in this study including household rainwater yield of 59 kL, connected roof area of 210 m^2 and tank volume of 4.2 kL. There is some degree of uncertainty that the average scenario would produce the average yield and this is evident with the simulated yield (48 kL) being 26% greater than the measured yield.

The sensitivity of yield estimates to model parameters was demonstrated in Chapter 3 and is critical to the connected roof area. The average connected roof area reported by Ferguson (2011) of 210 m^2 is excessive in relation to other surveys (White 2009) and this could account for the overestimate in simulation results. Also, Ferguson (2011) suggests that retrofitted systems are likely to have smaller connected roof areas, due to difficulties and added costs of connecting distant downpipes. Unfortunately, the distribution of new or retrofitted systems was not quantified in the survey, which would have assisted to verify this significant parameter.

Simulation results were verified by three independent analyses and are consistent or conservative with PURRS simulation throughout Australia, consistent with statistical analyses and end use studies for South-East Queensland but somewhat excessive for field measurements from Sydney households. Overall, this provides a reasonable verification of rainwater yield simulation estimates is demonstrated for these scenarios.

These results justify the decisions made to simplify aspects of the simulation model. These simplifications include: the use of a daily depth of initial loss from the roof catchment and first flush diverter, as opposed to an event-based approach; and the disregard of hydrologic losses from leaf separators.

4.7 Summary of rainwater tank modelling

This chapter discusses the development, calibration and validation of a mass-balance behavioural simulator (UrbanTank) for estimating the dual-duty performance of rainwater tanks. Suitable time-steps for model components were estimated and verified through the parameter sensitivity analysis. The simulator calculates roof runoff at six minute intervals to incorporate rainfall intensities within pluviograph observations; then aggregates runoff to determine hourly inflows which are combined with hourly water use estimates to calculate the hourly water balance of yield, overflow and environmental flow. Finally, with adaptive tanks, surplus stored water is estimated on a daily basis and if necessary, environmental flows occur over the next 24 hours.

The spill-before-yield model sequence was adopted as this approach overestimates tank overflow and underestimates rainwater yield with the magnitude of errors limited by the fine model time-step adopted. This approach is ideal for a conservative estimate of the dual-duty performance of rainwater systems. Also, estimates of rainwater yield were in agreement with other independent research.

Rainfall data in the form of pluviograph observations was examined for integrity. Adopted simulation periods of duration greater than 30 years were achieved for all capital cities excluding Brisbane, which was limited by available data. Long-term time-series of annual rainfall showed most cities are not experiencing a gradual increase or decrease in rainfall. Some exceptions were a steady slight increase in Darwin, a steady slight decline in Perth and a dry to wet oscillation with a frequency of 10 to 13 years in Sydney. Overall, the rainfall data should provide a reasonable estimate of long-term average conditions for rainwater harvesting in Australian capital cities.

Parameter values for roof hydrology were adopted from the conclusions of the literature review which had a mixed influence on model predictions in the sensitivity analysis in Chapter 3. These parameter values have been justified by the verification of model estimates to field measurements of rainwater yield and adopted practices for simulating rainwater tanks.

First flush interception values were adopted from the conclusions of the literature review which had a limited influence on model predictions in the sensitivity analysis in Chapter 3. Verification of model estimates also confirms these parameter values.

Average annual household water use was adopted from the conclusions of the literature review which has a strong influence on model predictions in the sensitivity analysis in Chapter 3. The adopted medium annual average household water consumption was 200 kL with lower and upper scenarios defined as 130 kL and 300 kL, respectively. Household water use components were defined from trending and average results in the literature and used to define three household rainwater demand scenarios.

Hourly diurnal patterns of internal and external household water use were studied and the mean of results in the literature was adopted in the model. The sensitivity analysis in Chapter 3 showed model estimates were unchanged by scenarios with and without water use patterns. However, the diurnal patterns are used universally as the sensitivity of model estimates is presumed to increase with smaller storage fractions, which will occur in modelling scenarios not yet examined.

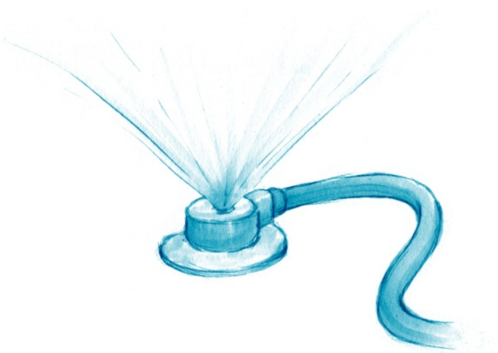
An adaptive approach for enabling environmental flow was proposed with the basis of sizing the environmental flow chamber to correspond to the frequency of rainfall, the severity of rainfall forecasts or a combination of both signals.

New performance metrics were introduced comprising supply independence, volumetric utility, environmental flow drought, environmental flow longevity, supply drought, supply longevity, imported household water and household rainwater harvest.

Finally, model estimates of rainwater yield were verified by independent field measurements in Brisbane and Sydney. Furthermore, estimates are in agreement with adopted practices for simulating rainwater performance throughout Australian capital cities. Therefore, UrbanTank is founded on field measurements from the literature and simulation results are largely in agreement with independent research.

Chapter 5 Outdoor Water Use

The variability of outdoor water use is a critical factor in estimating rainwater harvesting performance. This chapter introduces an Australian national approach to predict monthly patterns of local domestic outdoor water use from climatic indices of daily rainfall and maximum temperature. The model is verified by measured monthly water use at Adelaide, Bundaberg, Emerald, Fraser Coast, Gold Coast, Mackay, Melbourne, Newcastle, Perth and Toowoomba. Survey data represents periods prior to, during and after the millennium drought of 2001 - 2005 by discontinuously spanning 25 years from 1985 to 2010. A demand index is produced that predicts daily proportions of annual water use with 90% of the spatial and temporal variability being identified.



5.1 Introduction

The yield sensitivity analysis demonstrated the need for further investigation of the cause of seasonal change in outdoor water use. In Chapter 3, simulated rainwater yield estimates changed notably when the portion of outdoor water uses was varied. To qualify yield estimates and the results of this dissertation it is necessary to discover the cause of seasonal change in outdoor water use so that this relationship can be included in the simulation model outlined in Chapter 4, and this is the objective of this chapter.

Domestic water use comprises two components: *base demand*, which is predominantly constant and in most cases represents water use within the home (Orr *et al.* 2011); and *variable demand*, which varies seasonally and represents outdoor water use, such as irrigation and recreational use (Zhou *et al.* 2002). The reliability of supplies is dependent on outdoor demand (McMahon & Mein 1978; Mitchell *et al.* 2001) and this dependence is strongest in intermittent supplies, such as rainwater harvesting (Su *et al.* 2009). This is due to the potential for supply shortfall during periods of high demand. For this reason, only the variable component of water use is studied in this chapter.

Variability in outdoor water use at different locations is dependent on climate (Berk *et al.* 1980; Protopapas *et al.* 2000; Coombes 2002; Gato *et al.* 2007), together with socio-demographic settings (Race & Burnell 2004; Beal *et al.* 2010; Willis 2010), socio-economic settings (Coombes 2002; Loh & Coghlan 2003; Wasimi & Hassa 2011), household and property characteristics (Willis 2010), consumer trust (Jorgensen *et al.* 2009), attitudes towards water conservation (White 2009; Dolnicar & Hurlimann 2010; Willis *et al.* 2011a), local water governance policy (Campbell *et al.* 2004; NWC 2009) and other minor factors. With vast climatic variability between urban centres in Australia and recent periods of climate uncertainty, the climatic influences are of principal interest to this study.

The main climatic influences have been identified as rainfall and temperature together with investigations of humidity (Aly & Wanakule 2004) and evapo-transpiration (Campbell *et al.* 2004). During the years 2001 to 2005, vast regions of Australia experienced the millennium drought (DSEWPC 2006). This drought was so named due to a coincidence with the new millennium. In Australia drought can be severe. Therefore, investigating periods prior to, during and after drought is essential for a holistic view of water use.

This chapter investigates whether the monthly temporal pattern of outdoor water use at different climatic locations throughout Australia can be defined by a single parsimonious model related to daily observations of rainfall and maximum temperature. This approach allows for rapid and economic estimation of the broader reliability of water supplies, which is difficult to do using the localised and complex methods in the literature.

To achieve this aim, the methodology was: (1) obtain measured data on the historic monthly residential outdoor water use at locations that represent the breadth of climatic regions and spread of urban development throughout Australia, and demands at times prior to, during and after the millennium drought; (2) synthesise monthly water use measurements into a unit-base demand index to facilitate a comparative analysis of temporal and spatial aspects; (3) establish a simple model to predict the monthly temporal pattern of water use from daily observations of rainfall and temperature; (4) eliminate the dependence on localised calibration of the model by deriving local parameters from a national regression to rainfall and temperature statistics; and (5) apply the model to estimate long-term patterns of outdoor water use for Australian capital cities.

5.1.1 Literature review of water use modelling

As concluded in the literature review, common to the water use models discovered was a high dependence on local data in demand, climatic and/or demographic forms for regression and/or model training processes. Broad application of these methods to fulfil the scope of research would be impractical, due to excessive processing and data limitations. The alternative presents reduced data dependence and processing requirements.

5.2 Methodology

5.2.1 National outdoor water use surveys

To consider the broad response of residential outdoor water use to rainfall and temperature, several locations were selected to represent the climatic regions of Australia (Fig. 5-1 and Table 5-1).

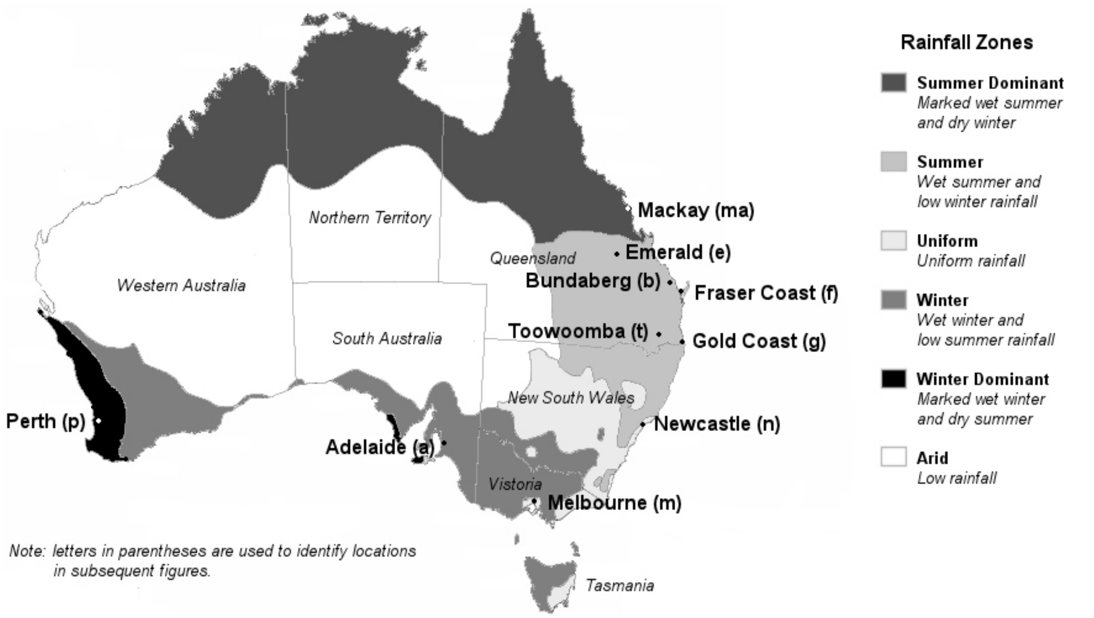


Fig. 5-1 Study locations and rainfall zones of Australia. Source adapted from (BoM 2011).

From the locations studied, the monthly outdoor water use was measured by four methods: (1) Dwelling meter reading at Fraser Coast (Cole 2011), Newcastle (Coombes 2002) and Perth (Loh & Coghlan 2003); (2) Utility bulk production at Adelaide (Barton & Argue 2005), Bundaberg (McLaughlin 2011) and Gold Coast (Willis et al. 2011b); (3) Utility bulk production adjusted by multivariate econometric analysis at Emerald, Mackay and Toowoomba (QDNR 2000); and (4) Quarterly utility bulk production adjusted by non-parametric aggregation (Coombes 2002) at Melbourne (Coombes 2009).

Table 5-1 Climate statistics and survey data for outdoor water use analysis

Site	Rainfall: Daily mean[b] (mm)	Rainfall: std. dev. (mm/d)	Temp.: Mean Max. [b] (°C)	Temp.: std. dev. (°C)	Survey period	Source
a	1.48	4.04	21.5	6.38	1997-02	(Barton & Argue 2005)
b	2.76	9.31	27.2	3.19	2009-10	(McLaughlin 2011)
e	1.63	8.19	29.7	5.13	1991-99	(QDNR 2000)
f	2.96	8.93	26.4	3.82	2008-09	(Cole 2011)
g	3.97	15.01	25.0	3.49	2008-10	(Willis *et al.* 2011b)
ma	4.41	17.78	26.4	3.69	1987-99	(QDNR 2000)
m	1.80	4.48	19.8	5.93	2003-04	(Coombes 2009)
n[a]	3.08	7.35	21.8	3.82	1991, 95 & 96	(Coombes 2002)
p	2.12	6.07	24.4	6.06	1998-01	(Loh & Coghlan 2003)
t	2.27	8.37	24.7	5.16	1985-99	(QDNR 2000)

[a] Data shown for calibration run 1995 only.

[b] Mean daily rainfall and daily maximum temperature derived from (BoM 2012d). Standard deviations of rainfall and temperature derived from simulation data only.

The length of water use data varies from one year at Fraser Coast, Bundaberg and Newcastle to greater than 10 years at Mackay and Toowoomba. This allows consideration of how the simulation duration may affect model performance. Also, to consider the response of water use to rainfall and temperature in times of drought, survey periods have been taken prior to, during and after the millennium drought of 2001 to 2005 (DSEWPC 2006).

The studied locations represent most climate regions of Australia, excluding the arid interior and wet tropics of far north Queensland (Fig. 5-1), where water use survey data was limited. A large variation in mean daily rainfall, ranging from 1.48 mm/d in Adelaide to 4.41 mm/d in Mackay can be seen (Table 5-1). These locations also display a large variability in daily rainfall, with standard deviations of 4.04 mm/d and 17.8 mm/d, respectively. Furthermore, rainfall in Adelaide is dominant in winter and in Mackay the dominant season is summer. Collectively, the study locations demonstrate the extremities of rainfall throughout major Australian population centres.

Where total water use figures were published, the internal portion, or non-seasonal use, was subtracted as a fixed amount per month derived as a percentage of annual demand (Zhou et al. 2002). Subtraction of internal use occurred at Emerald (42%), Mackay (61%) and Toowoomba (71%) in accordance with average annual demand breakdowns (QDNR 2000). The same process was applied on the Gold Coast, where internal use accounted for 87.3% of total demand for communities without greywater reticulation, during the summer of 2009 - 2010 (Willis et al. 2011b). In Bundaberg, the internal portion was not reported, so the Queensland mean of 65% was adopted, which was derived by averaging the abovementioned internal deductions.

5.2.2 Unit-based demand indices

To compare monthly water use data over the broad spatial and temporal investigation proposed, a common unit-base demand index is created by transforming the measured usage data by unit-normalisation which is determined with (5-1) where: n is the number of elements in the time-series data, X_t is the element value at time or sequence number t and XI_t is the transformed value or index (unitless), being the proportion of the sum of element values.

$$XI_t = \frac{X_t}{\sum_{t=1}^{n} X_t} \qquad \textbf{(5-1)}$$

In this way, the water use pattern for each location is expressed as a monthly proportion of annual demand. This transformation reveals the percentage of annual demand by month, which is a useful statistic for comparing water use patterns of times or locations with higher or lower annual demand. A similar approach is widely used where monthly values are normalised by the annual mean value and not the annual total (QDNR 2000), which prohibits monthly proportions of annual demand being derived.

5.2.3 Monthly water use modelling approach

The model presented in the chapter predicts monthly water use in the form of unit-based indices rather than actual water use estimates, thereby offering a simplified alternative to those mentioned in Section 2.6.1 of the literature. This approach reduces model inputs to local daily observations of rainfall and maximum temperature, which are readily available throughout Australia (BoM 2012d). It is widely recognised that the greatest water use occurs when temperature is high and rainfall is low, and that demand reduces as these extreme conditions weaken. Investigation of the difference between temperature and rainfall may be a good measure of the local monthly water use pattern, however, due to mismatched units, these climatic observations must be normalised to create dimensionless indices before their difference can be logically calculated. Therefore, the unit-normalisation approach is again applied.

Gato et al. (2007) demonstrates that a temperature threshold affects outdoor water use in Melbourne, with temperatures above the threshold generally causing an increase in demand, whereas temperatures below show no such relationship. Due to climate variability, the threshold is expected to vary by location. The local temperature threshold TT (°C) is therefore subtracted from daily temperature observations T_d (°C) before unit-normalisation is applied to create the daily temperature index TI_d (unitless) as determined with (5-2). Subsequent discussion shows that estimation of local TT values can be eliminated by a national regression to the standard deviations of daily maximum temperature.

$$TI_d = \frac{\max\{0, (T_d - TT)\}}{\sum_{d=1}^{n} \max\{0, (T_d - TT)\}} \qquad \textbf{(5-2)}$$

The short-term effect of rainfall on external water use can be observed over a period of days (Coombes 2002). Consistent with root zone moisture antecedence behaviour of moderately to imperfectly drained soils (Macleod 2008), rainfall is accumulated over four consecutive days to account for this effect. By this approach, rainfall on the three days preceding the current day R_d is included in the daily rainfall index RI_d (unitless), and determined with (5-3).

$$RI_d = \frac{R_d + R_{d-1} + R_{d-2} + R_{d-3}}{\sum_{d=1}^{n}(R_d) \times 4} \qquad \textbf{(5-3)}$$

It is anticipated that the trigger for outdoor water use may occur when the rainfall index is less than the temperature index, as this would represent the onset of hot dry conditions (Fig. 5-2).

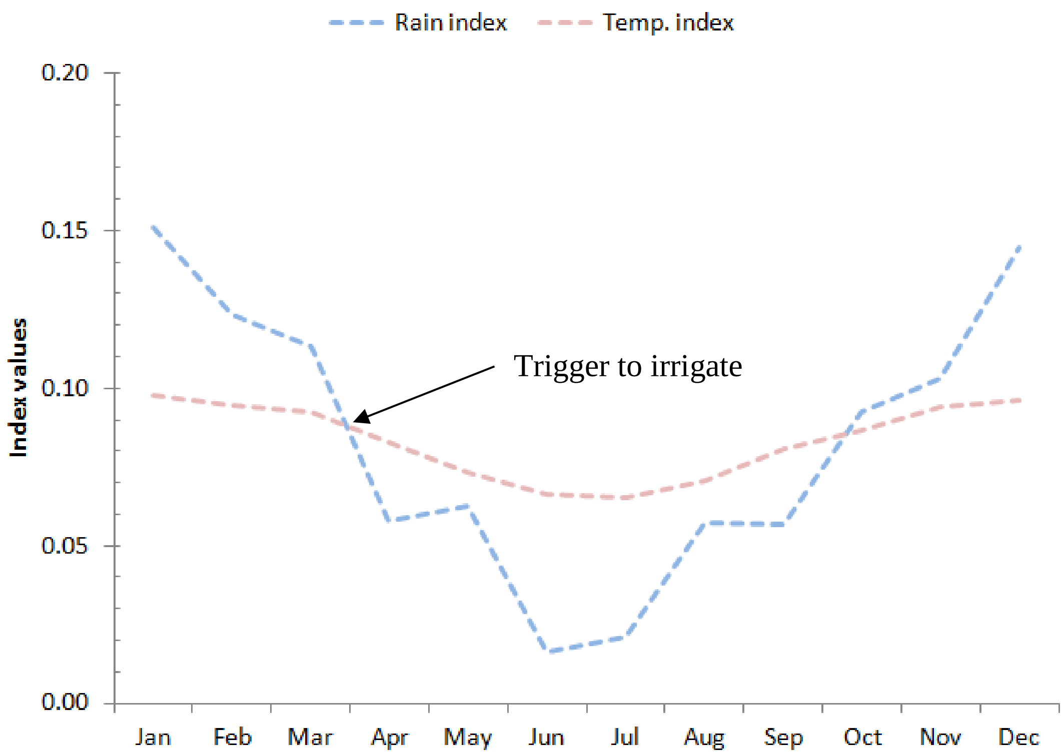


Fig. 5-2 Trigger to irrigate based on rainfall and temperature indices

Also, it is expected the water use sensitivity to the difference between these indices is unlikely be consistent at all locations, and a calibration factor will be necessary. By standard deviation, rainfall variability is higher than temperature (Table 5-1). Therefore, this calibration factor will be known as a rainfall sensitivity parameter *RS* and will be applied to the demand condition DC_d of the model which is determined with (5-4). Subsequent discussion shows that estimation of local *RS* values can be eliminated by a national regression to the standard deviations of daily rainfall.

$$DC_d = \begin{cases} \max(0, TI_d - RI_d), & RI_d \times RS \leq TI_d \\ 0, & otherwise \end{cases} \tag{5-4}$$

The annual sum of demand values derived from the demand condition is not expected to have a magnitude of one, as is needed to be compatible with the observed demand indices. Therefore, a unit-normalisation transformation is applied to derive the predicted daily outdoor demand index EDI_d, as determined with (5-5).

$$EDI_d = \frac{DC_d}{\sum_{d=1}^{n} DC_d} \tag{5-5}$$

Finally, summation of daily predictions by month produces final model predictions of monthly demand indices or, in other words, percentages of annual water use by month.

5.2.4 Monthly water use model calibration

Eight of the ten locations were chosen to calibrate the model**,** leaving Bundaberg, Fraser Coast and additional surveys in Newcastle for model validation. This allowed the model to be calibrated to a broad range of climatic zones. Calibration was achieved through iterations of adjusting *TT* and *RS* values to develop a series of water use patterns that provide the maximum coefficients of determination when compared to observed monthly demand indices. Each location was calibrated separately.

5.2.5 Eliminating local parameter dependence

To remove dependence on local calibration and provide a means for broader application, the relationship between the localised model parameters, *TT* and *RS,* and local climatic statistics was investigated. Due to non-normality observed in the time-series data of daily rainfall and daily maximum temperature, mean absolute deviations and median absolute deviations were examined together with standard deviations.

5.2.6 Monthly water use model validation

The model was validated by inspecting the predicted demand indices against the observed demand indices for Bundaberg, Fraser Coast and Newcastle, while adopting the national regression of *TT* and *RS* parameter values. As an additional measure, the *TT* and *RS* parameter values that returned the best prediction were plotted on the national regression charts to ensure that they reside between 5% and 95% confidence limits.

5.2.7 Long-term water use patterns

To assist with establishing the long-term performance of rainwater systems the model is applied to derived long-term outdoor water use patterns in Australian capital cities. The six minute rainfall data discussed in Chapter 4 was aggregated into a daily time-series and daily maximum temperature observations were obtained from the Bureau of Meteorology (Table 5-2).

Table 5-2 Adopted weather stations for demand analysis

Station	Description	District	Opened	Status	Records[a]
023090	Kent Town	Adelaide Plains	1977	open	99.9%
040913	Brisbane	Moreton South Coast	1999	open	99.8%
070014	Canberra airport comparison	Sthn Tablelands Gburn-Monaro	1939	closed	99.9%
014015	Darwin airport	Darwin-Daly	1941	open	99.1%
094029	Hobart (Ellerslie Rd)	Southeast	1882	open	91.1%
086282	Melbourne airport	East Central	1970	open	100%
009021	Perth airport	Central Coast	1944	open	99.9%
066062	Sydney (observation Hill)	Metropolitan (E)	1858	open	99.7%

[a] Maximum temperature records were obtained on 18/11/2011 and the date of the final observation varied by location. The completeness of records is calculated for the complete archive, which in some stations did not commence during the opening year listed.

Minimal missing temperature observations were discovered in most locations and were limited to periods of short duration. Missing values were replaced by substituting preceding values. The adopted simulation period is mostly limited by the availability of pluviograph records, as discussed in Chapter 4. However, in Hobart a period of missing temperature data just prior to 1920 was avoided despite adequate pluviograph records.

The variability of mean daily maximum temperature in Australian capital cities (Fig. 5-3) is comparatively less than the variability of annual rainfall (Fig. 4-4). The effects of climate change can be seen with temperatures increasing in recent years in Adelaide, Canberra, Melbourne, Perth and Sydney, albeit marginally. The adopted simulation periods provide a strong representation of the long-term average maximum daily temperature for most capital cities of Australia.

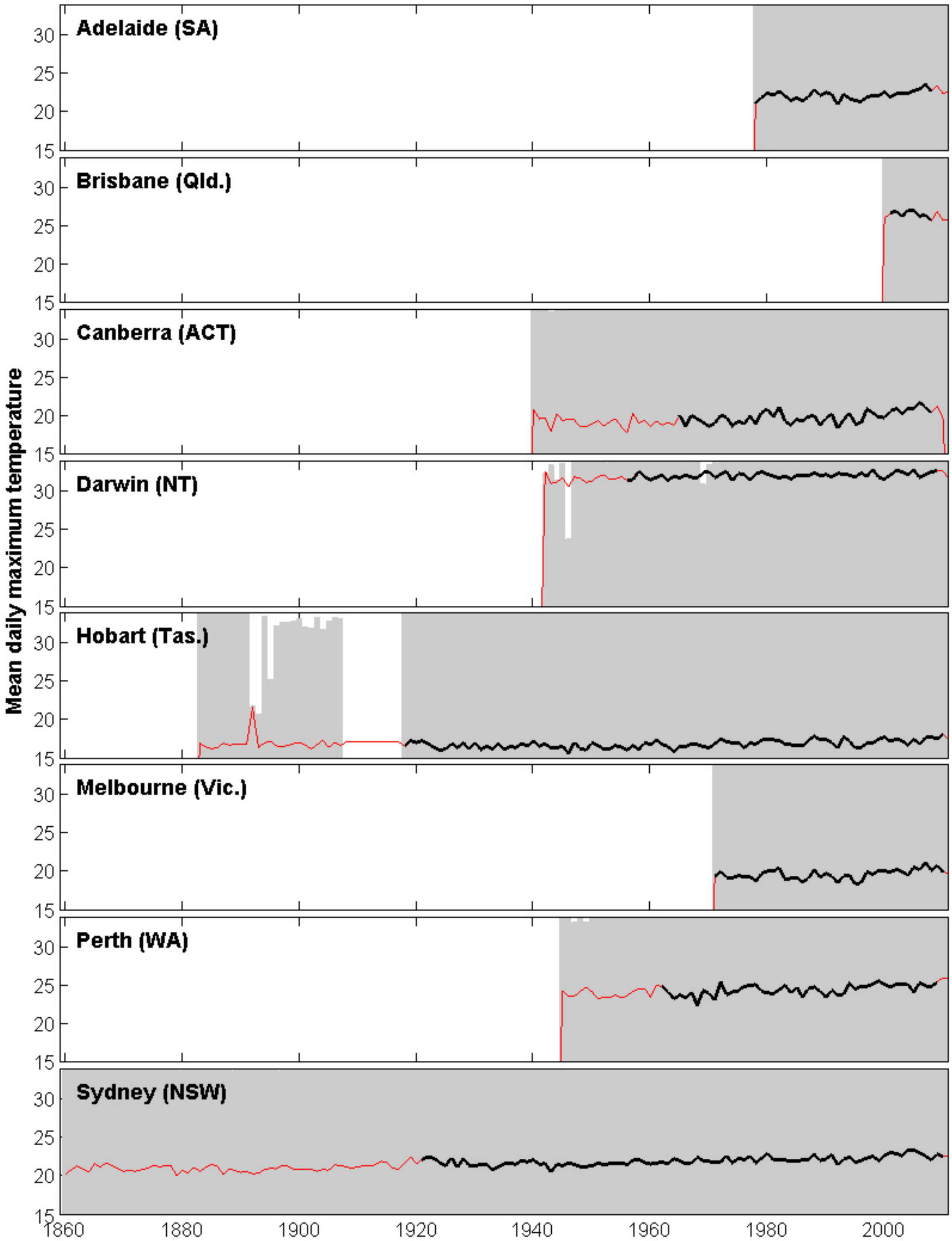


Fig. 5-3 Mean daily maximum temperature observations (ºC) in Australian capital cities (**red**), completeness of annual records (**grey bars**) and adopted input data (**black**).

5.3 Monthly water use model results and discussion

Regression results are shown by coefficients of determination (R^2), the mean sum of residual errors (MSE), Durbin Watson's serial correlation of residuals (DW) significance (*p*), skewness of residuals (*g*) and, where sufficient data exists, Chi-Squared (χ^2) and the degrees of freedom (d.f.).

From the statistics examined, the standard deviations of daily maximum temperature and daily rainfall provide the strongest TT and RS regression among all study sites (Fig. 5-4 and Fig. 5-5). All calibration and validation values reside within the confidence limits, and a reasonable national regression is shown with R^2 values of 0.57 and 0.68. Also, low negative autocorrelation of residuals is evident with DW values of 2.60 and 2.97, which indicates the order and method of regressions is suitable. Furthermore, independent analysis of the temperature threshold at Melbourne at which outdoor water use is influenced (Gato et al. 2007), also closely follows the national regression presented here. Gato's result is noted using a black 'm' in Fig. 5-4.

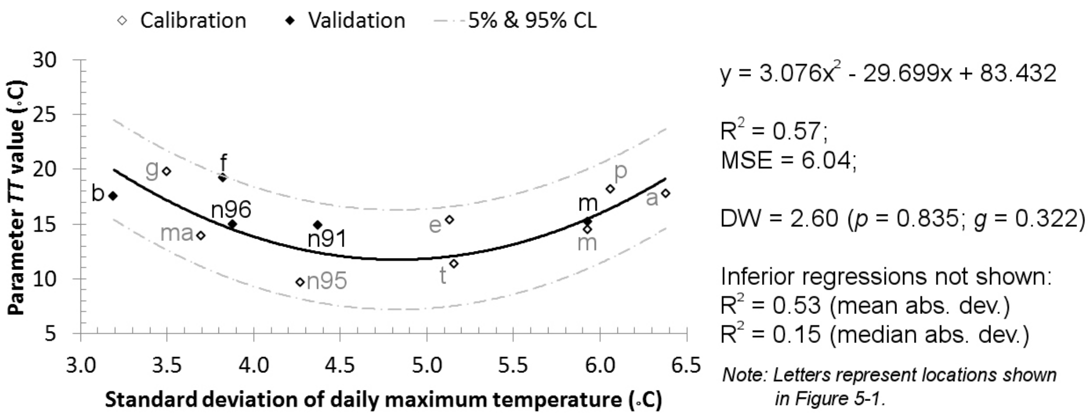


Fig. 5-4 National regression of temperature threshold parameters *TT* discovered in calibration and validation scenarios

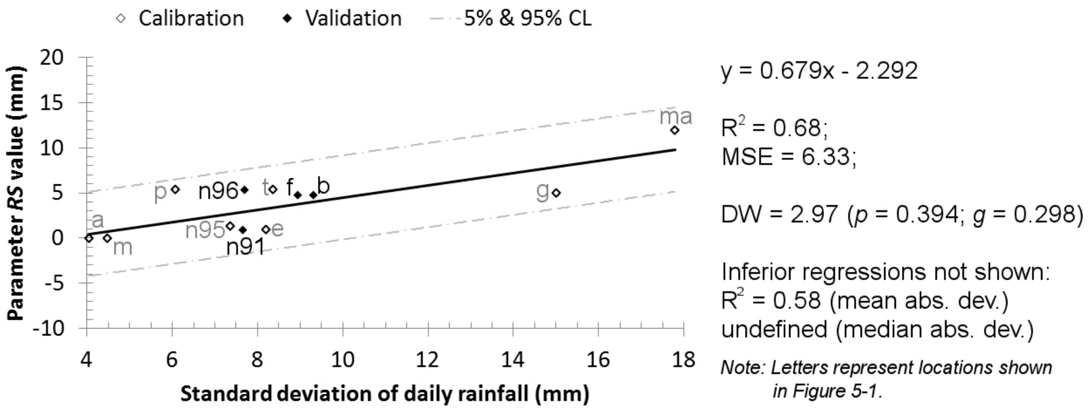


Fig. 5-5 National regression of rainfall sensitivity parameters *RS* discovered in calibration and validation scenarios

Therefore, it is demonstrated that local calibration of *TT* and *RS* parameters can be avoided by the developed relationships to the standard deviations of daily maximum temperature σ_T (°C) and daily rainfall σ_R (mm/d), and can be determined with (5-6) and (5-7), respectively.

$$TT = 3.076{\sigma_T}^2 - 29.699\sigma_T + 83.432 \quad \textbf{(5-6)}$$

$$RS = 0.679\sigma_R - 2.292 \quad \textbf{(5-7)}$$

In all locations studied, as the rainfall variability increases, the *RS* value, and water use sensitivity, also increases (Fig. 5-5). As the validation points are clustered in the lower domain, further investigation at locations with higher standard deviations of rainfall is recommended.

While adopting the national regression for *TT* and *RS* parameters, the model can identify 83% of the spatial and temporal variability of demand patterns with the distribution of predicted values closely follows that of the observed values (χ^2 = 3.39; d.f. = 2; p = 0.184) (Fig. 5-6), and residuals are approaching a normal distribution (Fig. 5-7). Furthermore, there is only weak evidence of positive serial autocorrelation (DW = 1.72), which is a good result for time series regression.

Inspection of the calibration points only demonstrates that results are well-scattered and accuracy is maintained throughout the domain (R^2 = 0.90 and not shown in Fig. 5-6 for clarity). Validation results are weaker, as expected, and generally are well-scattered. There is limited evidence of high demand indices being under-predicted during validation.

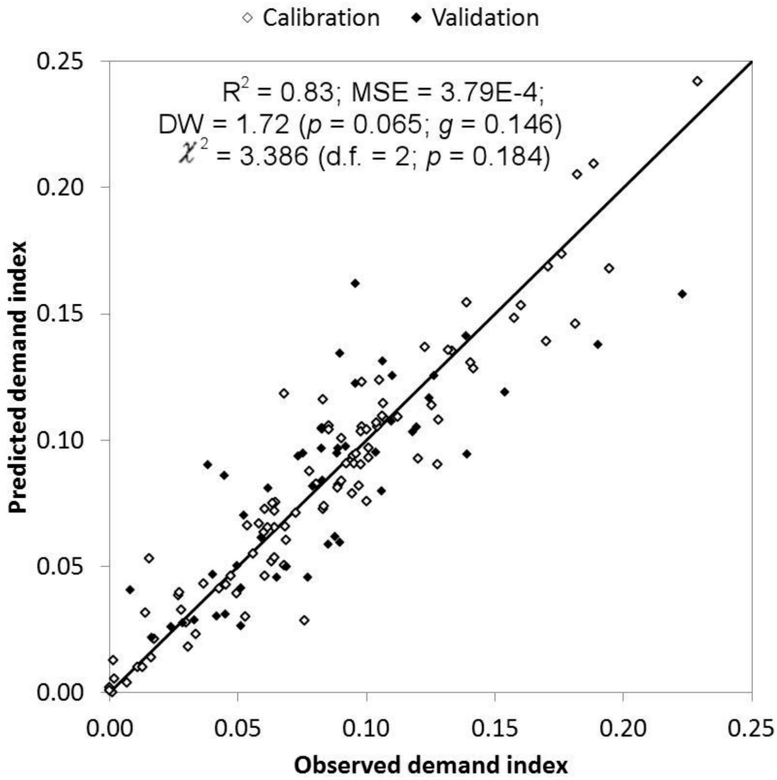


Fig. 5-6 Predicted against observed monthly demand indices for calibration and validation scenarios

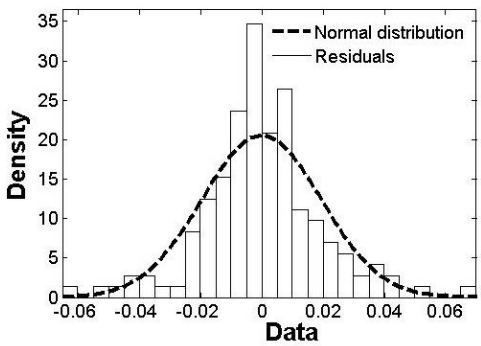


Fig. 5-7 Approaching normal distribution of estimated demand residuals

Adopting the national regression for *TT* and *RS* parameters, Adelaide, Mackay, Melbourne and Perth all display strong calibration regression ($0.92 \leq R^2 \leq 0.97$) and limited positive autocorrelation of residuals ($1.13 \leq DW \leq 1.81$), which demonstrates rigorous prediction (Table 5-3 and Fig. 5-8) throughout the varied climatic regions of Australia. Also, strong regression is achieved regardless of the method used for measuring demand, such as residential meter surveys in Perth ($R^2 = 0.95$), utility bulk water production in Adelaide ($R^2 = 0.97$), utility bulk water production adjusted by multivariate analysis in Toowoomba ($R^2 = 0.92$) and adjusted by non-parametric aggregation in Melbourne ($R^2 = 0.95$) (Table 5-3).

The most atypical water use patterns are observed in the Gold Coast and Newcastle, where their is absence of a distinct rain season and rainfall patterns appear to be more random. In these locations weaker regressions were observed ($R^2 = 0.58$ and $R^2 = 0.73$, respectively) (Table 5-3). Given the irregularity of these patterns and limited positive auto correlation of residuals ($1.62 \leq DW \leq 1.80$), these results are also favourable.

Table 5-3 External demand model parameters and regression statistics

Site	**Scenario**	***TT***	***RS***	**R^2**	**MSE**	**DW**	***p***	***g***
Pre drought								
a	C	19.1	0.45	0.97	2.2e-4	1.79	0.31	-0.50
e	C	12.0	3.27	0.58	8.8e-5	2.76	0.40	-0.39
ma	C	15.7	9.79	0.92	9.2e-5	1.13	0.01	0.62
n91	V	14.9	2.90	0.79	3.7e-4	1.62	0.19	-0.46
n95	C	12.7	2.70	0.73	3.7e-4	1.99	0.66	-1.09
n96	V	14.5	2.93	0.46	7.9e-4	1.94	0.53	1.04
p	C	16.4	1.83	0.95	2.1e-4	1.40	0.08	-0.21
t	C	12.1	3.38	0.92	5.6e-5	1.19	0.03	0.94
During Millennium drought								
m	C	15.5	0.75	0.95	2.9e-4	1.81	0.30	0.19
Post drought								
b	V	20.0	4.03	0.66	6.2e-4	1.59	0.14	0.57
f	V	14.9	3.77	0.71	5.3e-4	1.46	0.11	0.12
g	C	17.2	7.91	0.58	6.0e-4	1.80	0.40	0.31

Note that model scenarios are calibration (C) and validation (V).

The significance of *TT* is seen in most sites by the demand pattern closely following the temperature index (Fig. 5-8). However, *TT* does not completely define the water use pattern as demonstrated by results in the Gold Coast, Mackay and Newcastle scenarios (Fig. 5-8). In these locations, the pattern tends to mirror the rainfall index. This phenomenon also occurs in Adelaide and Perth but may not be immediately apparent due to strong correlation with the temperature index.

Also, in Melbourne the rainfall index is approaching uniformity and the water use pattern is almost entirely defined by the temperature index (Fig. 5-8). Alternatively, Emerald and Toowoomba show subtle water use patterns which closely follow both temperature and rainfall indices. Collectively, these locations demonstrate three unique responses in water use habits: 1) closely follow temperature pattern; 2) mirror rainfall pattern; and 3) follow rainfall and temperature pattern. The use of climate indices has allowed these three unique responses to be incorporated into a single parsimonious model.

Overall, reasonable validation results are achieved ($0.46 \leq R^2 \leq 0.79$; $1.46 \leq DW \leq 1.94$) (Table 5-3 and Fig. 5-9). The weakest and strongest results occurred in Newcastle. With these mixed results, an investigation of changes to the *TT* and *RS* values was considered.

TT and *RS* values for the 1991, 1995 and 1996 Newcastle studies remained fairly constant at 12.4, 12.7, and 14.5 °C and 2.90, 2.70 and 2.93 mm, respectively (Table 5-3). This suggests that the response of outdoor water use to rainfall and maximum temperature has not materially altered over this six year period.

Investigation of model predictions in periods prior to, during and after the millennium drought results in performance with $0.46 \leq R^2 \leq 0.97$, $R^2 = 0.95$ and $0.58 \leq R^2 \leq 0.71$, respectively (Fig. 5-8 and Fig. 5-9). This suggests generally the weaker predictions occurred in periods after the drought, which may be evidence of recent water conservations programs adjusting our water use behaviour. However, this cannot be confirmed without investigating water use patterns at each location before and after the drought.

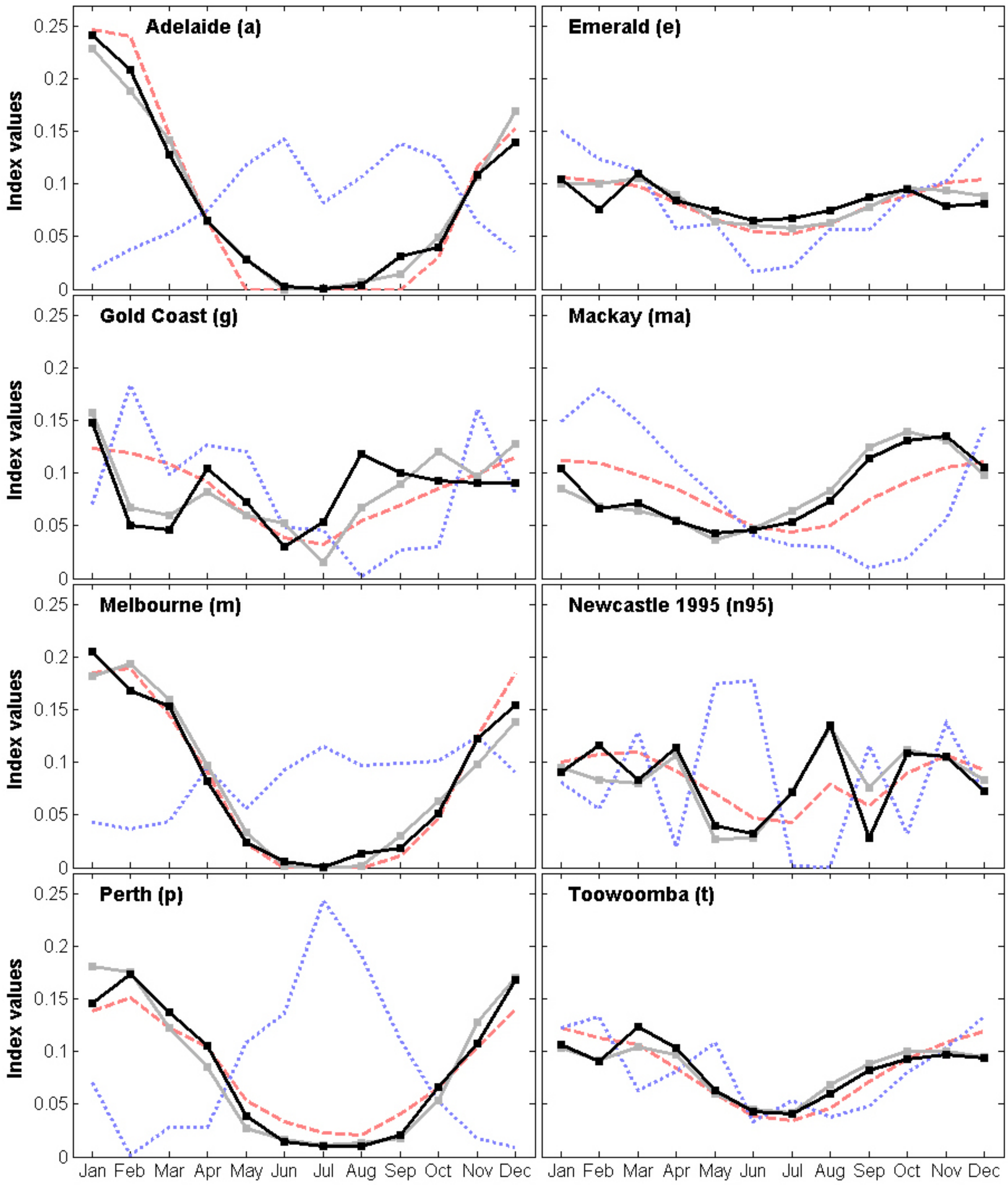


Fig. 5-8 Calibrated estimates of mean monthly demand indices (**black**) derived from rainfall indices (**dotted blue**) and temperature indices (**broken red**) and compared to measured demand indices (**gray**).

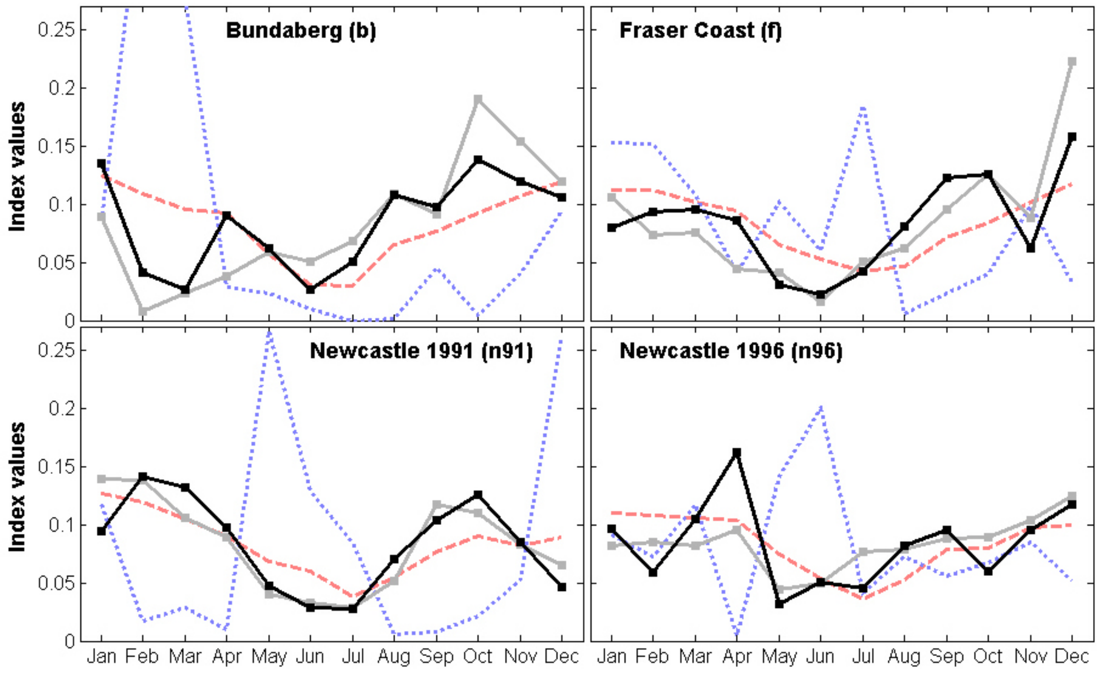


Fig. 5-9 Validated estimates of mean monthly demand indices (**black**) derived from rainfall indices (**dotted blue**) and temperature indices (**broken red**) and compared to measured demand indices (**gray**).

The duration of the simulations is shown to affect model performance. Locations with a survey duration limited to one year have returned some of the weakest results ($0.46 \leq R^2 \leq 0.73$), locations with medium-term durations of 2-9 years have mixed results ($0.58 \leq R^2 \leq 0.97$) and locations with greater durations have consistent results ($R^2 = 0.92$). This suggests the model performs satisfactory in the short-term but is best suited for longer-term analysis.

There is no profound evidence to support the assumption that climatic affects on water use habits have remained consistent over the long-term. Actually, the results are somewhat contrary by suggesting climatic affects may be weakening post millennium drought, in favour of cultural change potentially resulting from water conservation programs (England 2009). However, assuming the impact of rainfall and temperature on outdoor water use has not changed, the long-term annual average outdoor water use can be estimated (Fig. 5-10).

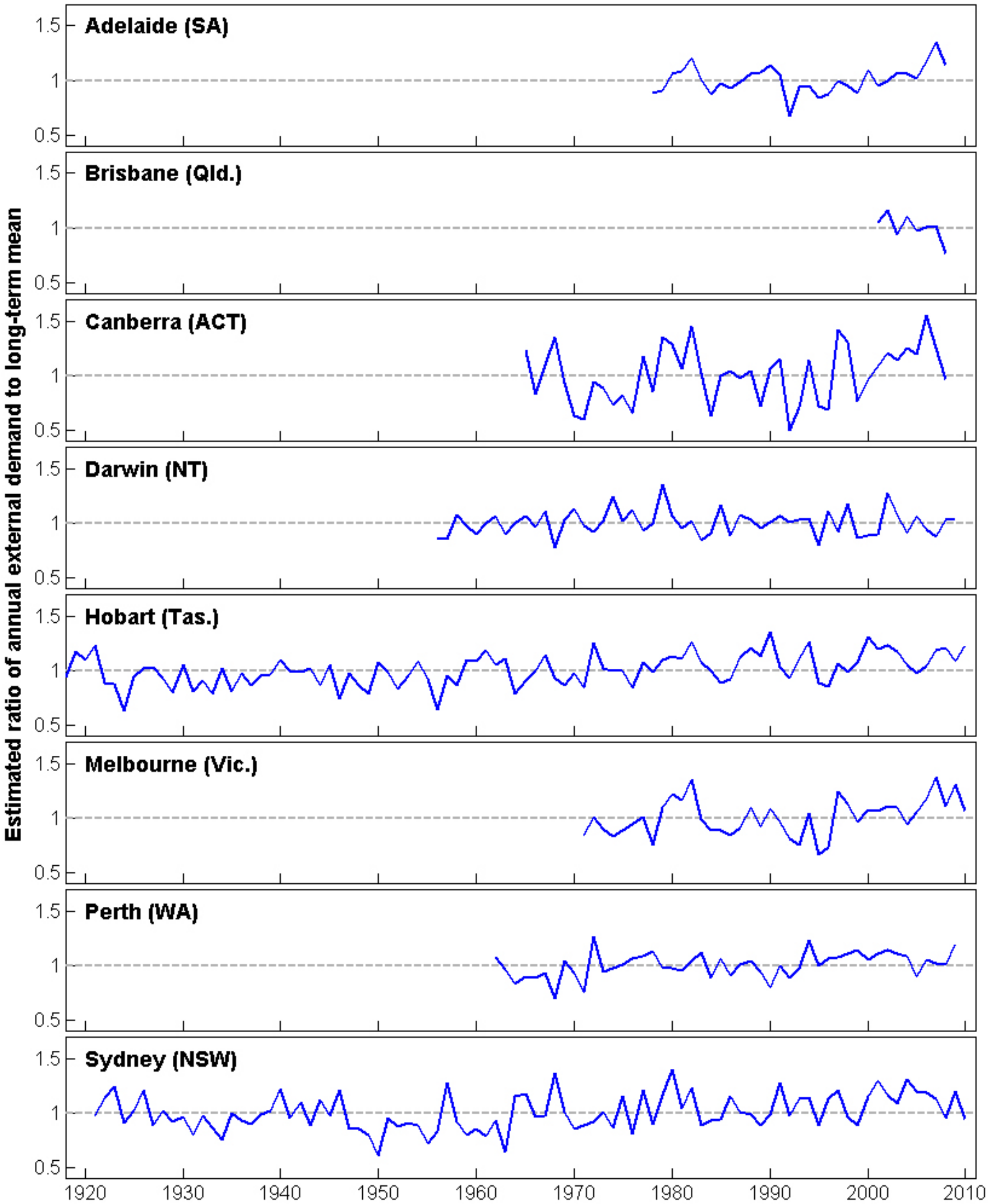


Fig. 5-10 Estimated ratio of annual outdoor water use to long-term annual mean derived from the relationship between recent water use habits and daily rainfall and temperature observations.

Potentially, most capital cities show similar deviations in estimates of annual outdoor water use and no cities display obvious trends that climate change will increase outdoor water use. Hobart does however show a slight increase despite meagre temperature change (Fig. 5-3). This increase is possible to see from the extensive simulation period which is not available at all locations.

Comparatively mild behaviour is estimated in Darwin, which is a surprising result, considering annual rainfall is highly varied in the Tropical North (Fig. 5-3). This may suggest the frequency of rain events is reasonably consistent while the magnitude is not. Similarly, estimations for Sydney are less chaotic than expected, but the periodicy of peak water use is consistent with annual rainfall patterns discussed in Chapter 4.

Estimates in Canberra are the most chaotic which can be related to the higher variability of mean daily maximum temperature, comparative to the other capital cities (Fig. 5-3). Therefore, from estimations of long-term outdoor water use in Australian capital cities, there is potential that water use habits may be more sensitive to temperature change than rainfall. Finally, these long-term estimates are applied to derive a distribution of monthly water use patterns (Fig. 5-11).

The outdoor water use patterns are predicted to closely follow the temperature index for most capital cities. Brisbane and Darwin are exceptions and this is due to low winter rainfall and moderate range in daily maximum temperature (Fig. 5-11). Sydney displays the greatest variability which results from the combination of rainfall that is relatively uniformly distribution and a limited range in maximum temperature. The narrowest distribution is in Perth where winter rainfall is highly dominant and a strong temperature range also exists. Finally, the long-term estimates in Adelaide, Melbourne and Perth are consistent with the calibrated predictions of the model, and likewise, Brisbane is consistent with the Gold Coast.

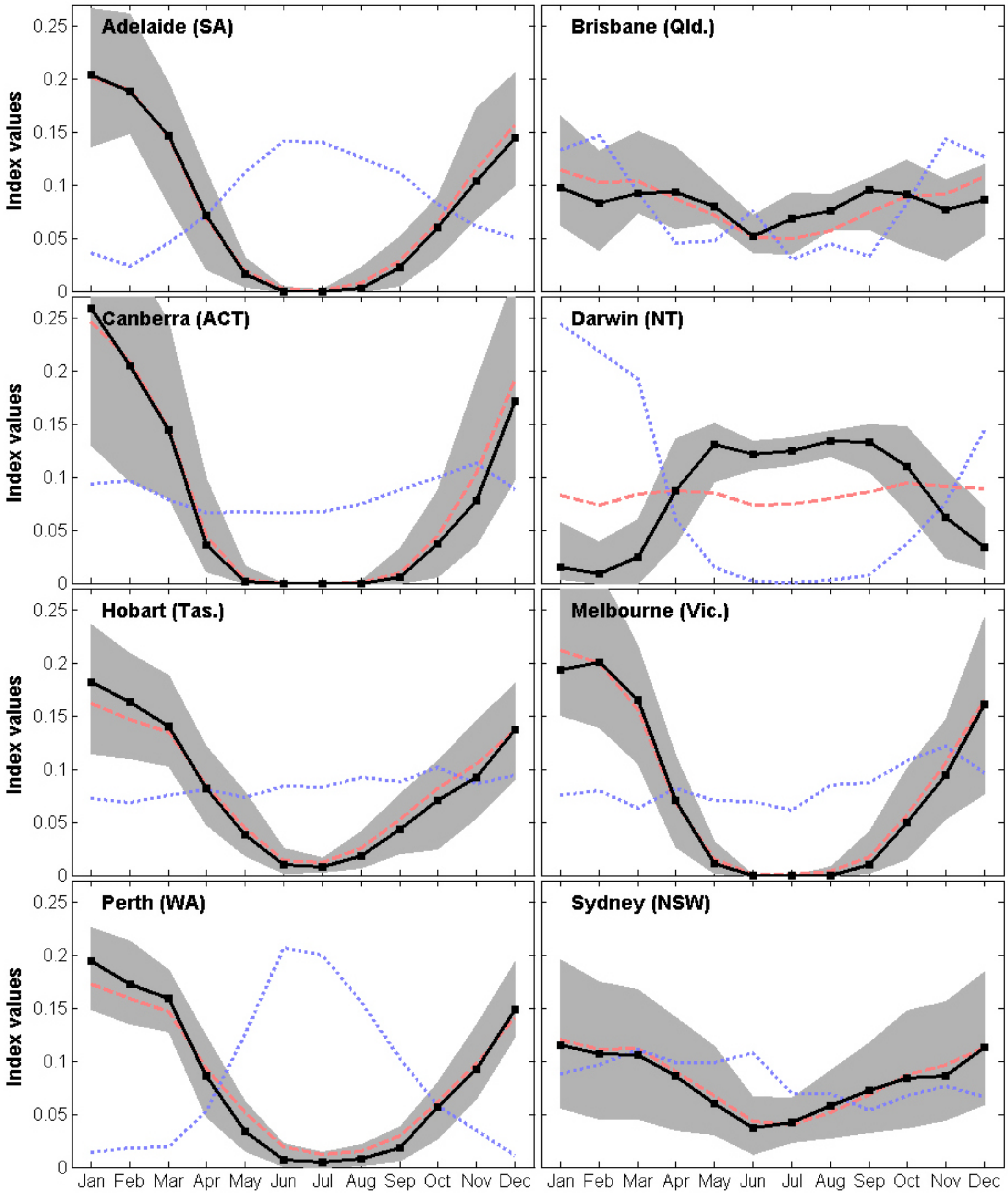


Fig. 5-11 Estimated long-term mean monthly demand distribution between 0.1 to 0.9 quantile (**gray**); and long-term mean monthly demand indices (**black**), rainfall indices (**dotted blue**) and temperature indices (**broken red**) of Australian capital cities.

5.4 Summary of monthly water use modelling

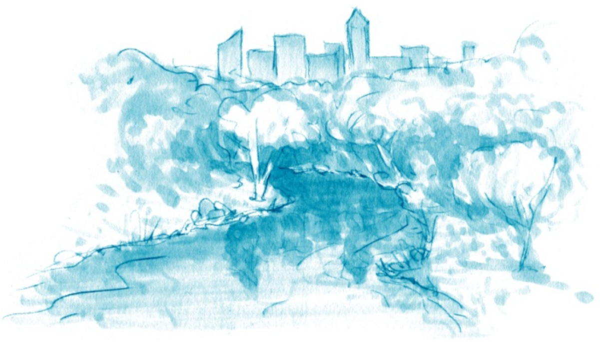
A single parsimonious model is introduced that predicts the monthly proportion of annual outdoor water use at various locations in Australia, from the difference between daily local temperature and rainfall indices. The broad climatic regions and urban spread throughout Australia have been represented with few exceptions. Also, as the calibration and validation data discontinuously spans the 25 year period from 1985 to 2010, water use habits prior to, during and after the millennium drought of 2001 to 2005 have been represented. The model shows a strong overall regression (R^2 = 0.90) in studies where local calibration is eliminated thorough national regression of model parameters to climate statistics. Inclusion of validation studies gives an overall performance of R^2 = 0.83 (χ^2 = 3.39; d.f. = 2; p = 0.184).

Further results from the study are: (1) the accuracy of mean monthly predictions generally increases as the number of years studied increases; (2) predictions are generally weaker in studies taken after the millennium drought, which may suggest water use habits are changing and may become less sensitive to environmental factors; (3) a temperature threshold at which outdoor water use is influenced is apparent in the studied locations; (4) the water use sensitivity to rainfall varies by location and can be defined by a linear relationship to the standard deviation of daily rainfall; (5) atypical water use patterns were the most difficult to predict and can occur in locations with non-seasonal rainfall; (6) model parameters are expected to remain reasonably constant over time; (7) the long-term annual variability in outdoor water use is estimated to be less affected by changes in rainfall than temperature with the most stable annual patterns observed in locations with high variability of annual rainfall; and (8) the long-term monthly distribution of outdoor water use is estimated to closely follow the temperature index in most locations and exceptions are where winter rainfall is limited.

Further research is recommended to include model validation at sites with higher standard deviations of daily rainfall, supported by calibration with measured water use at finer resolutions of daily or weekly timescales. Measured data prior to, during and after the millennium drought should also be applied to verify whether water use habits have changed in response to water conservation programs, and whether model parameters change with time.

Chapter 6 Dual-Duty Assessment of Rainwater Tanks

The environmental benefit index by Walsh (2012), which is founded on a new generation of stormwater management objectives aimed at protecting stream health, is applied to demonstrate the dual-duty performance of rainwater tanks in capital cities throughout Australia. A sensitivity analysis of leaking rainwater tanks confirms the hypothesis that the dual-duty performance can be improved by generating environmental flows.



6.1 Introduction

A global view of rainwater harvesting reveals widespread application to alleviate water scarcity. However, the catchment management position also offers a variety of applications from managing storm induced landslides in forest catchments by mitigating stormwater discharge with rainwater tanks (Wang *et al.* 2008), to the antithesis of limiting rainwater abstraction and maintaining minimum flows for ecological and humanitarian needs (Ngigi 2003).

Common to these studies, and many others previously mentioned, is the desire to restore the stream hydrology to pre-urban or natural conditions. This desire is often based on understanding of ecological limits to hydrologic alteration (Poff *et al.* 2010). Stream hydrology comprises principally of two components: *baseflow*, which is the gradual dewatering of the catchment that may discontinuously occur between rain events and consists of subsurface flow through natural topographic flow paths; and *surface runoff*, which results from recent rain events and usually has a comparatively short duration and large discharge.

The impacts of urbanisation modify these aspects of stream hydrology to produce flashy characteristics with increased frequency, magnitude, and annual volume of surface runoff, together with reduced baseflow. Overall, stream ecosystems are degraded by greater annual volume of flow, reduced recession and increased flow intermittency (Walsh *et al.* 2010), which these water bodies are particularly vulnerable to (Arthington *et al.* 2010). Together with degraded water quality it is not surprising the outcome is often very bleak.

However, the scope of this dissertation is limited to volumetric analysis of rainwater tanks, which precludes assessments at the catchment scale that may involve detailed surveys of vegetation, terrain, geology, soil permeability, bedrock topology and other factors that influence the natural occurrence, magnitude and duration of stream baseflow (Graham & McDonnell 2010), and surface flow (Boughton 2004).

Therefore, the aim of the chapter is to establish a method to measure the efficacy of rainwater tanks to restore aspects of pre-urban stream hydrology in Australian capital cities. Only the urban runoff contribution from roof area connected to rainwater tanks is considered. Thus runoff from other impervious surfaces would require treatment by other measures at street, estate and/or end-of-pipe scales. The environmental benefit and supply independence metrics are then combined to estimate the dual-duty performance sensitivity of leaking rainwater tanks.

6.2 Assessing pre-urban stream hydrology

Significant rainfall is lost or absorbed in natural catchments by saturating vegetation cover, infiltrating into soils, flooding depression storage and evapotranspiration from plants. Generally once all storages are overwhelmed, surface flow occurs and is subject to similar continued abstractions while travelling downslope, into streams and beyond. General relationships between these abstractions and average annual rainfall have been developed to include rainfall and evapotranspiration loss curves for catchments throughout the globe (Fig. 6-1), which was recently reviewed for cold climates with minor changes recommended (Komatsu *et al.* 2011). This work is also in agreement with rainfall and runoff plots for catchments throughout Australia (Fig. 6-2).

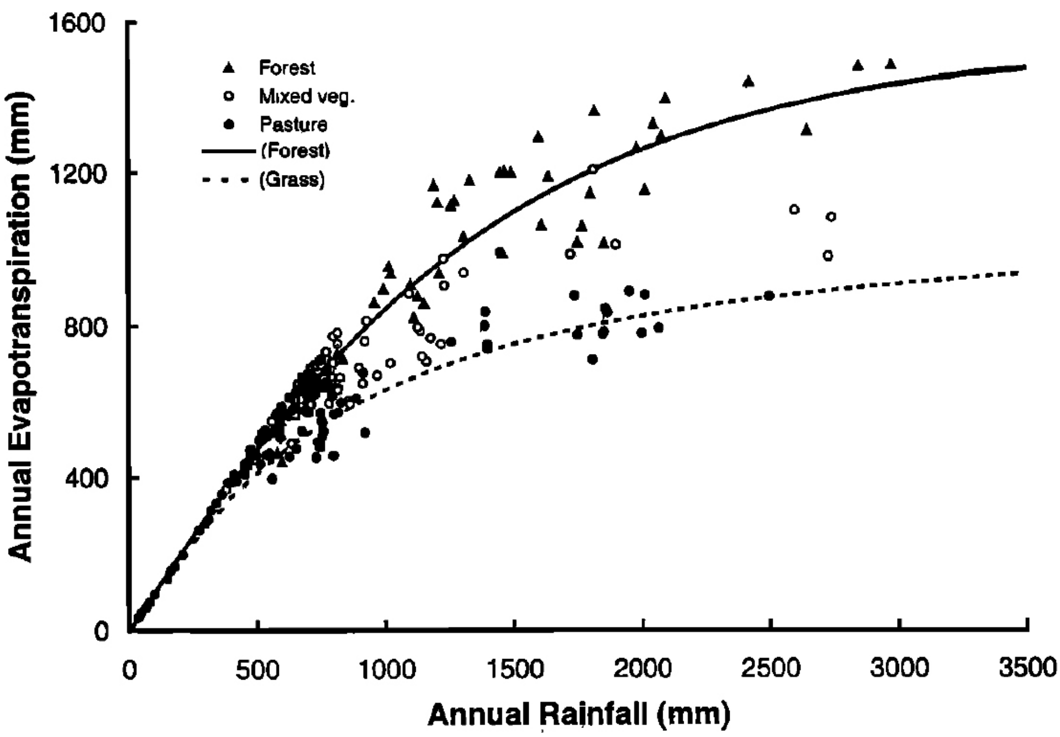


Fig. 6-1 Evapotranspiration loss curves for global catchments. Adapted from: (Zhang *et al.* 2001)

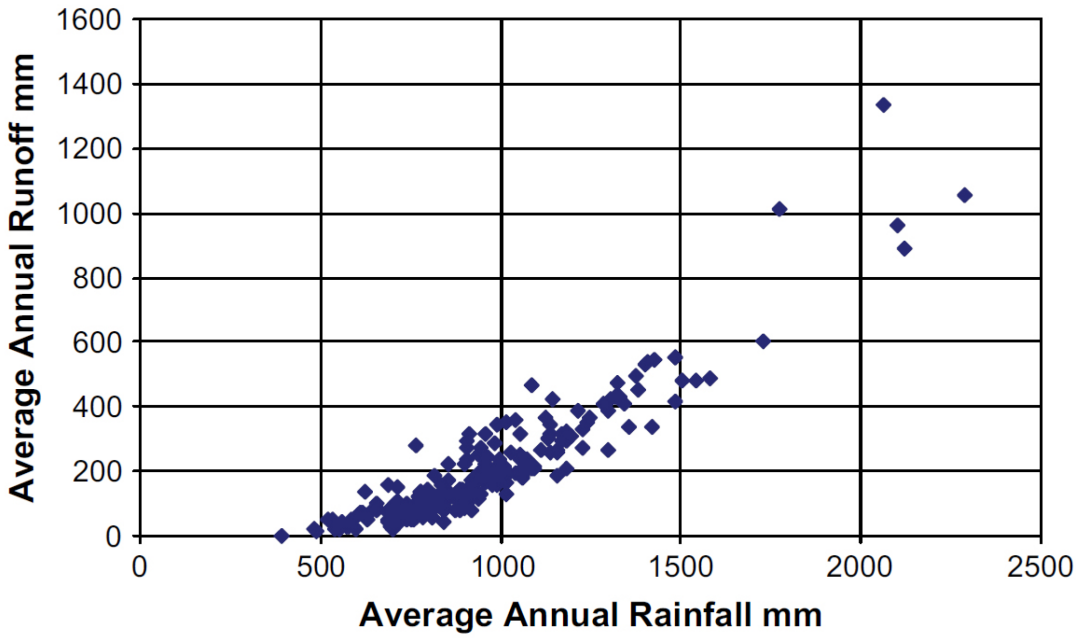


Fig. 6-2 Rainfall to runoff relationship for Australian catchments source: (Boughton & Chiew 2007)

Investigations of small hill slope catchments (0.09 to 3.8 ha), show very little surface runoff can occur (Graham & McDonnell 2010). Under these conditions, lateral subsurface flow is significant to stream hydrology and is consistent with rainfall to runoff relationships for larger catchments (Boughton & Chiew 2007).

Recently, a method to examine the environmental benefit of allotment-scale WSUD projects was developed and applied to assess proposals for restoration of Little Stringybark Creek in Melbourne. The environmental benefit index EBI (unitless) is available online (Walsh *et al.* 2012) and founded on a new generation of stormwater management objectives aimed at protecting stream health (Walsh *et al.* 2010). The index is derived from the mean of four sub-indices, each based on the maintaining hydrological conditions that stream ecosystems are particularly vulnerable to (Poff *et al.* 2010). Flow conditions include frequency of surface runoff, volume of sub-surface flow, water quality and total volume of flow, as described in Walsh *et al.* (2010).

6.2.1 Flow-frequency sub-index

The increased frequency of hydraulic disturbance that result from urbanisation is identified as the primary driver for stream degradation (Walsh *et al.* 2005b). The flow-frequency sub-index was established to estimate compliance by runoff days from rainwater tanks, or other WSUD projects, with the natural flow-frequency conditions for the catchment. A simplified flow-frequency sub-index is adopted for this research context that disregards the standardisation of impervious area, due to the entire catchment of rainwater tanks being impervious.

The simplified flow-frequency sub-index FFI (unitless) is based on the number of runoff days per year from scenarios including a rainwater tank R_t, an equivalent natural catchment R_n and an equivalent urbanised catchment R_u, which Walsh *et al*. (2010) presumes to be 50% impervious. FFI can be determined with (6-1).

$$FFI = 1 - \max\left({(R_t - R_n)}/{(R_u - R_n)}, 0 \right) \tag{6-1}$$

Adapted from (Walsh *et al.* 2010)

An FFI of one demonstrates compliance with pre-urban conditions and lower values represent excessive frequency of runoff events. Walsh *et al.* (2010) reports annual runoff days under natural and urban conditions in Melbourne are 12, but noted this was a likely overestimate, and 121, respectively. Average annual runoff days were estimated for Australian capital cities (Table 6-1) based on a daily rainfall to runoff threshold of 15 mm for natural catchments (Walsh *et al.* 2005b) and 0.4 mm for urban catchments (Chapman & Salmon 1996).

A discrepancy is noted in rain days for natural and urban conditions in Melbourne with lower calculations than published by Walsh *et al.* (2010) of 6 and 83, respectively. This is reasonable considering different weather stations and observation periods were adopted, due to the scope of research. The annual average rainfall applied in this study was 48% less.

Table 6-1 Average annual runoff days for Australian capital cities

City	Weather station	Rainfall[a] (mm/y)	R_n (days)	R_u (days)
Adelaide (SA)	23090	518	8	95
Brisbane (Qld.)	40913	874	17	86
Canberra (ACT)	70014	559	11	70
Darwin (NT)	14015	1583	34	89
Hobart (Tas.)	94029	578	8	114
Melbourne (Vic.)	86282	467	6	83
Perth (WA)	09021	694	14	85
Sydney (NSW)	66062	1147	22	111

[a] Average annual rainfall determined from simulation periods (Fig. 4-4).

6.2.2 Water quality sub-index

The water quality sub-index assesses discharge compliance for total nitrogen, total phosphorus and total suspended solids against guidelines for fresh and marine waters (ANZECC & ARMCANZ 2000). The scope of the proposed research, which is limited to volumetric assessment of rainwater tanks, precludes water quality assessment. However, as the literature review demonstrated, untreated runoff from roof surfaces or overflow from rainwater tanks is typically compliant with water quality guidelines for discharge. Whereas runoff from other urban surfaces is likely to be of lower quality and necessitate treatment before discharge into receiving waters (Brodie 2007). Therefore in the context of the proposed research, the water quality sub-index can be disregarded from the simplified environmental benefit index.

6.2.3 Filtered flow volume sub-index

The duration and water quality of baseflow in streams should be increased to avoid flow intermittency with excessive pollutant shock loading which can be detrimental to stream ecology. The filtered flow volume sub-index measures the potential contributions to filtered sub-surface flows or baseflows under different scenarios and demonstrates compliance with natural conditions. Again in this application, the standardisation of impervious area is disregarded. A simplified equation for estimating the filtered flow volume sub-index FVI (unitless) is based on unit area estimates of filtered flow from forest catchments FV_{forest} (L/y/m^2) and pastured catchments $FV_{pasture}$(L/y/m^2) that are derived from the relationship between rainfall and evapotranspiration (Fig. 6-1), together with the unit area filtered flow from the proposed retention system FV_t (L/y/m^2) and is determined with (6-2).

$$FVI = \begin{cases} {FV_t}/{FV_{forest}}, & FV_t < FV_{forest} \\ \max\left(0,1 - {(FV_t - FV_{pasture})}/{FV_{forest}}\right), & FV_t > FV_{pasture} \\ 1, & otherwise \end{cases} \tag{6-2}$$

Adapted from (Walsh *et al.* 2010)

With this approach, all stream flow in forested and pastured catchments is considered filtered flow as impervious surfaces are absent. Therefore, filtered flow estimates are not based on separation of baseflow from the total streamflow. A FVI of one demonstrates filtered flow volumes are within estimates of forested or pastured catchments. Lower indices indicate filtered flow is insufficient or excessive. A zero value indicates filtered flow is possibly greater than the combined estimates from forested and pastured catchments.

The discharge from first flush diverters will not be included in the filtered flow volume as this flux only occurs during rainfall and contains the highest pollutant concentration, both of which are uncharacteristic of filtered sub-surface flow. Therefore, it is recommended that discharge from first flush devices is disposed of locally via a gravel soak away drain or passive irrigation of a small garden bed.

Providing environmental flow from the rainwater tank is compliant with the water quality guidelines, then FV_t would consist of this water flux. The release rates would be restricted to emulate the gradual nature of stream baseflow and this would exclude environmental flows from calculations of runoff days from the system. If in the unlikely case environmental flows are not compliant by flow rate and/or water quality than a small scale WSUD treatment system would be necessary and the design of which is beyond the scope of the proposed research.

Unit area FV values and runoff coefficients RC were estimated for Australian capital cities with hypothetical catchments either completely pastured or forested (Table 6-2), based on the empirical relationship between annual rainfall and annual evapotranspiration (Fig. 6-1).

Table 6-2 Unit area annual filtered flow volume for Australian capital cities and runoff coefficients

City	Forested		Pastured	
	FV_{forest} (L/y/m^2)	RC_{forest} (-)	$FV_{pasture}$ (L/y/m^2)	$RC_{pasture}$ (-)
Adelaide	28	0.05	96	0.19
Brisbane	112	0.13	287	0.33
Canberra	34	0.06	114	0.20
Darwin	455	0.29	818	0.52
Hobart	38	0.07	123	0.21
Melbourne	21	0.04	76	0.16
Perth	61	0.09	181	0.26
Sydney	218	0.19	474	0.41

6.2.4 Volume reduction sub-index

The volume reduction sub-index VRI (unitless) measures the capacity to retain excessive runoff on the catchment that is generated from introducing impervious surfaces. It is therefore based on the excess runoff volume generated from a unit impervious area V_e (L/y/m^2) and the equivalent unit area volume of water harvested by the rainwater tank or lost through evapotranspiration V_c (L/y/m^2). Again, disregarding the standardisation of impervious area, the simplified form of VRI can be determined with (6-3). An index of one demonstrates all excessive runoff is retained on the catchments and lower values indicate some excessive runoff is discharged into receiving waters.

$$VRI = 1 - {(V_e - V_c)}/{V_e} \qquad \textbf{(6-3)}$$

Adapted from (Walsh *et al.* 2010)

In the case proposed here, V_c would consist of rainwater yield Y, first flush diversion FF and rainfall-runoff losses RRL from the roof catchment. This is based on these water fluxes being removed from stormwater runoff either by consumption, infiltration, evaporation or, with the minor case of roof leaking and splashing at the perimeter, being absorbed by pervious surfaces adjacent to the house. The excess runoff volume is estimated for Australian capital cities (Table 6-3) based on the relationships between annual precipitation P (mm/y) and impervious area runoff coefficients RC_{imp} (unitless) which can be determined from (6-4).

$$RC_i = 0.234 + 0.203 \times \log(P) \tag{6-4}$$

(Walsh *et al.* 2010)

Table 6-3 Impervious runoff coefficients and unit area excess runoff volume for Australian capital cities

City	$\boldsymbol{RC_{imp}}$ **(-)**	$\boldsymbol{V_e}$ **(L/y/m^2)**
Adelaide	0.82	566
Brisbane	0.83	611
Canberra	0.79	406
Darwin	0.88	937
Hobart	0.79	419
Melbourne	0.77	339
Perth	0.81	498
Sydney	0.85	758

6.3 Simplified environmental benefit index

The simplified environmental benefit index EBI (unitless) is derived from the mean of sub-indices including frequent-flow FFI, filtered flow volume FVI and volume reduction VRI. The index is simplified by disregarding the water quality sub-index and the standardisation of imperviousness. The EBI will be applied to measure the efficacy of rainwater tanks to restore pre-urban hydrology where a value of one demonstrates full compliance and lower values correlates with lower performance.

All water fluxes of leaking and adaptive rainwater tanks have been included in the EBI (Fig. 6-3).

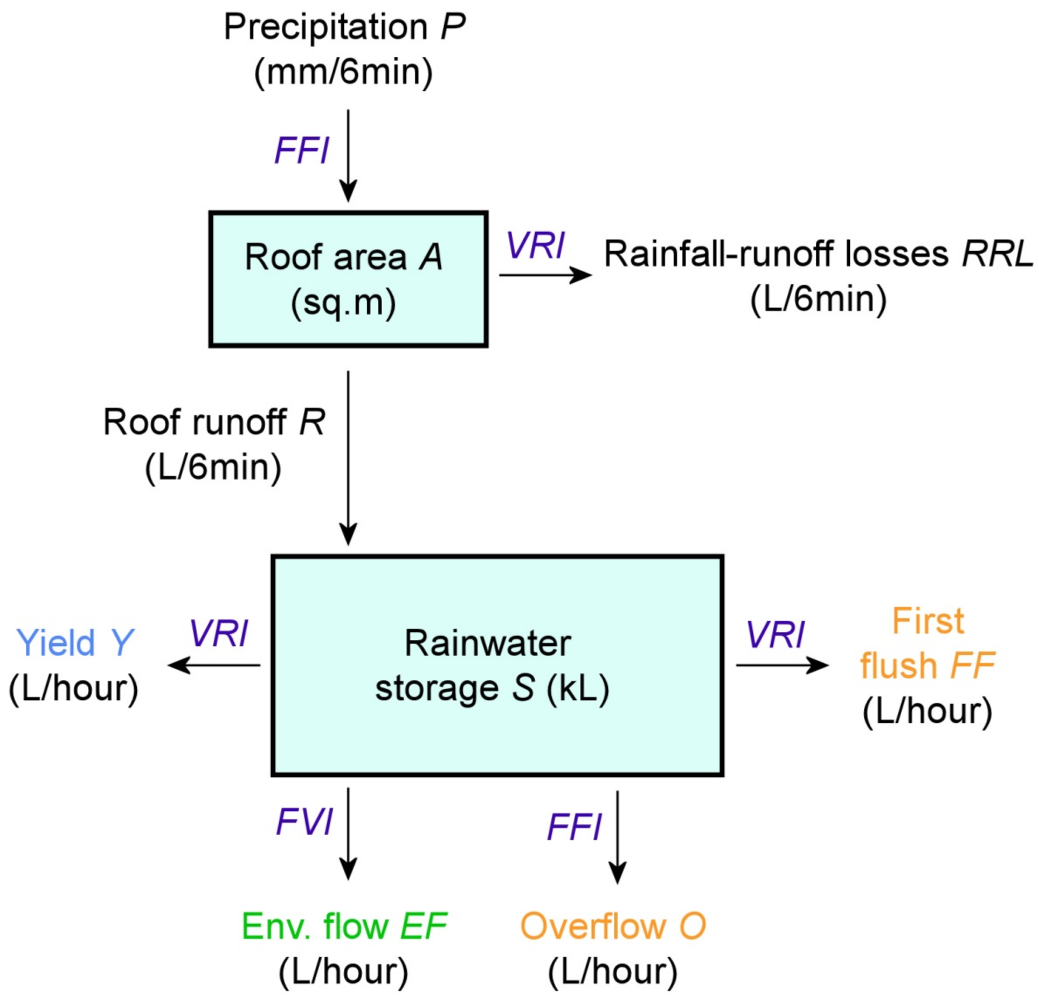


Fig. 6-3 Water fluxes of the rainwater tanks that produce environmental flows and corresponding sub-indices of the environmental benefit index

6.4 Dual-duty performance sensitivity analysis

Following on from the yield sensitivity analysis of conventional rainwater tanks that was discussed in Chapter 3, the dual-duty performance of leaking rainwater tanks will be examined as the final phase in this chapter. These results will apply the new performance metric of supply independence SI and volumetric utility VU introduced in Chapter 4.

6.4.1 Dual-duty sensitivity analysis of leaking rainwater tanks

Three metrics are considered in the sensitivity analysis of the leaking rainwater tanks comprising volumetric utility VU which is the mean of supply independence SI and the environmental benefit index EBI. A base scenario of parameters was established (Table 6-4), together with commonly adopted parameter ranges and the broader parameter domains. Also, the parameter change indices ΔP_i (Table 6-4) were determined following the methodology introduced in Chapter 3.

Table 6-4 Parameter values for dual-duty sensitivity analysis

	Adopted			Domain		
Parameter	**Min**	**Base**	**Max**	**Min**	**Max**	$\Delta \boldsymbol{P_i}$
Average annual rainfall P (mm/y)[a]	507	552	921	200	2000	0.23
Env. flow rate Q_{EF} (L/day)[b]	100	300	900	0	1300	0.62
Env. flow chamber volume V_{EF} (kL)	0.25	1.25	2.5	0	9	0.26
Roof area A (m^2)	100	150	200	25	300	0.36
Total tank volume V_t (kL)	2.5	5	7.5	2	10	0.63
Average annual rainwater demand D_r (kL)	44	87	176	20	350	0.40

[a] Adopted annual rainfall from last four years of simulation records in Hobart, Melbourne and Perth for minimum, base and maximum scenarios, respectively.
[b] Upper valid environmental flow rate determined from 24 hour infiltration of medium clay at 0.36 mm/hr (eWater 2011) over 150 m^2.

Estimates from UrbanTank (Fig. 6-4) consistently demonstrate SI is lower than the EBI for leaking rainwater tanks. SI values will rarely exceed 0.3, irrespective of the tank type (conventional, leaking or adaptive), while it remains standard practice to connect only a fraction of household water fixtures to rainwater supply. In Section 4.6, it was demonstrated that rainwater yield estimates were in close agreement with field measurements and consistent with statistical analyses, end use studies and adopted simulation practices.

High EBI scores were discovered with most scenarios above 80% compliance. This is an encouraging result but leaves little to no opportunity for improvement from adaptive approaches for managing environmental flow. Parameters are listed in order of decreasing sensitivity to VU and the three sensitivity indices shown in parentheses are SSI values for the metrics of SI, VU and EBI, respectively.

All metrics displayed a negative correlation to mean annual rainfall which demonstrates that this statistic is a poor indicator of potential rainwater yield and capability to restore aspects of pre-urban stream hydrology. The three rainfall scenarios were taken from regions with increasing seasonality of rainfall; rainfall in Hobart is non-seasonal, in Melbourne is mildly summer dominant and is winter dominant in Perth. Therefore, the dual duty performance may be negatively correlated to the seasonality of rainfall and this will be examined in Chapter 9.

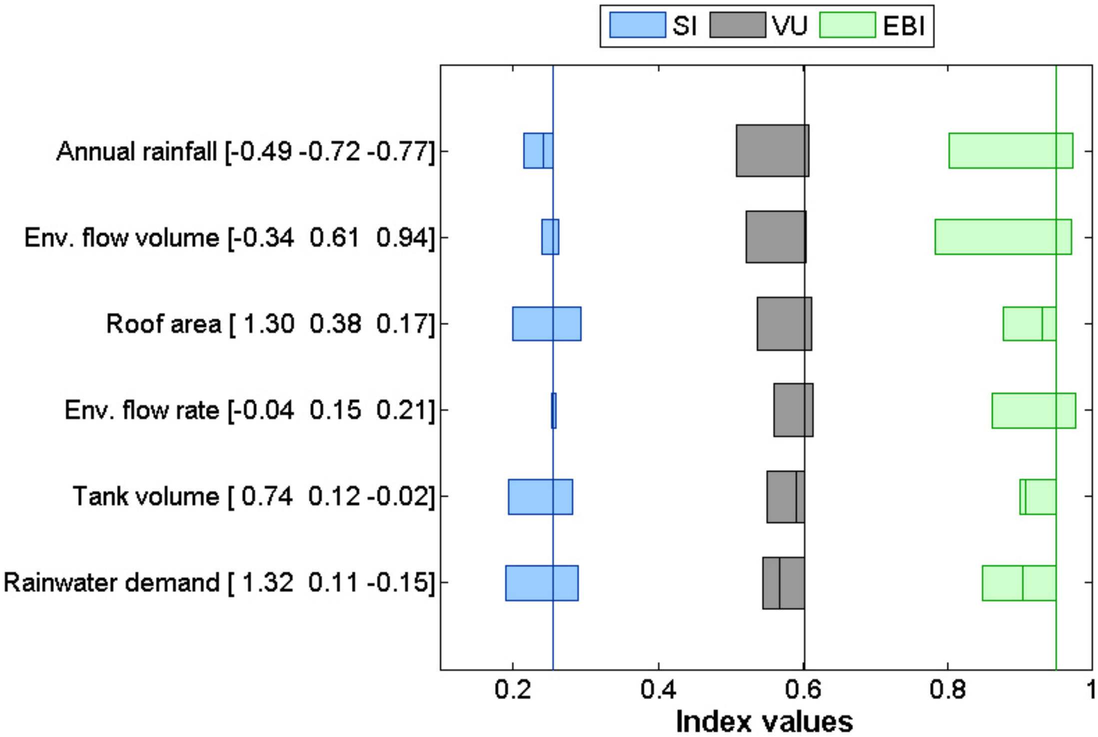


Fig. 6-4 Dual-duty parameter sensitivity analysis of leaking rainwater tank showing SSI values in parentheses

Encouraging results were found for changes to the environmental flow chamber volume. For the scenarios examined, the chamber volume was increased from 250 L to 2.5 kL; consequently, SI reduced moderately by 0.006, while the EBI increased significantly by 0.189. This is not surprising as it was previously stated in the yield sensitivity analysis of Chapter 3 that rainwater yield is not particularly sensitive to tank volume.

Also not surprisingly the roof area is a significant parameter with a strong positive correlation to SI. However, further investigation which is not shown here revealed an upper limit exists were the flow-frequency sub-index declined at a greater rate than SI improved. This is due to the excessive frequency of overflow from large rooves and small rainwater tanks. For the base scenario this turning point was located at approximately 200 m^2. However, under these conditions an increase in the environmental flow rate could improve performance.

Changes to the environmental flow rate also revealed some encouraging results. As expected, SI is slightly negatively correlated to this parameter while the EBI is positively correlated, which demonstrates environmental flow from rainwater tanks will not significantly reduce rainwater yield and will provide an environmental benefit. In the case here, the environmental flow rate was increased from 100 L/d to 900 L/d which resulted in a meagre drop in SI of 0.007 while the EBI increased significantly by 0.114. Further analysis of larger flow rates revealed a reduction in both SI and EBI eventually occurs. This is related to the presumption in the EBI that annual filtered flows higher than that produced from pastured catchments would be detrimental to stream health. Therefore, an optimum environmental flow rate exists and for the base case this was 100 L/day which is consistent with adopted values for high density urban settings in other independent studies (Burns *et al.* 2010). It should be noted that where situations allow, baseflow rates should be determined following analysis of the catchment characteristics, and particularly the response to urbanisation (Hamel *et al.* 2013).

Similar results were obtained for scenarios that examined total tank volumes. In this case, the volume of the environmental flow chamber remained fixed at 1.25 kL while the total tank volume increased from 2.5 kL to 7.5 kL. The EBI is negatively correlated to total tank volume due to lower environmental flow from larger tanks. A small tank produces environmental flow more frequently and with a larger annual volume, while the increase in overflow frequency was only mild. Therefore an optimum tank volume could potentially exist for a nominated catchment and rainwater demand.

Interesting results were obtained for the model response to rainwater demand with SI showing a strong positive correlation while EBI is negatively correlated. Analysis of the sub-indices within EBI revealed the flow-frequency sub-index increases from 95% to 100% compliance which is consistent with expectations that higher rainwater demand would reduce the frequency of tank overflow. However, the filtered-flow volume sub-index is negatively correlated to rainwater demand with compliance dropping from 100% to 47%. This is however positively correlated to the reduction in environmental flow that occurs from tanks with higher rainwater demand, in this case, environmental flow reduced from 6 kLto 2 kL/y. Also, the increase in demand enabled the volume reduction sub-index to reach 107% which means the rainwater tank was compensating for the excess runoff generated from impervious surfaces additional to the connected roof area. From these results, it is likely that an optimum rainwater demand will exist and this will be studied in Chapter 8.

Results from the scenario with a limited environmental flow chamber should be similar to a conventional rainwater tank. This suggests the research hypothesis may be valid, so far as dual-duty performance increases when environmental flows are released from rainwater tanks. However, given the high environmental benefits of leaking rainwater tanks it is unlikely that an adaptive approach to managing environmental flows will provide superior performance. Collectively, the sensitivity of system performance to change in environmental flow rate and chamber volume demonstrates high potential for dual-duty rainwater tanks.

6.5 Summary of dual-duty assessment of rainwater tanks

A simplified form of the environmental benefit index EBI has been presented and applied to assess the sensitivity of dual-duty performance estimates of rainwater tanks to design parameters. The sensitivity analysis partly confirms the research hypotheses that the dual-duty performance can be improved by enabling environmental flows from leaking rainwater tanks.

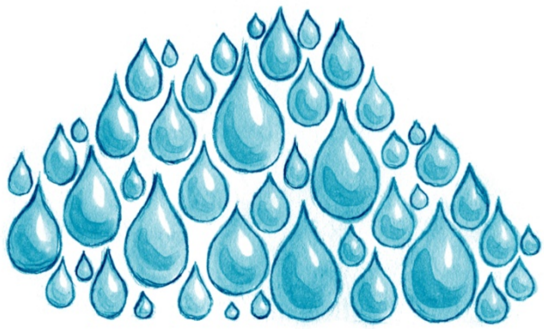
Analysis of environmental benefits from rainwater tanks was limited to the contributions of urban runoff from roof areas connected to rainwater tanks. Treating runoff from other impervious surfaces is essential for a holistic approach to restoring pre-urban hydrology.

Further conclusions are it is likely that optimum values exist for the environmental flow rate, rainwater demand and tank volume, which will be examined in Chapter 8; and it is likely the dual-duty performance will be negatively correlated with the seasonality of rainfall, which will be examined in Chapter 9.

Chapter 7 Supplementing Archives of Daily Rainfall Forecasts

It is proposed to actively manage environmental flows from rainwater tanks based on the severity of rainfall forecasts. Unfortunately the duration of forecast archives is limited and needs to be supplemented to facilitate the long-term assessment necessary for the research scope. Four methods are examined for supplementing daily archives of rainfall forecasts by combining historic rainfall observations with error behaviour of current forecast techniques (as at 2012).

Using a hindcast approach, the accuracy of gridded forecasts is examined for Australian capital cities with time horizons up to four days and accumulation mean periods up to eight days.



7.1 Introduction

In an attempt to find the ultimate performance of dual-duty rainwater tanks, it is proposed to adaptively control environmental flows based on the severity of rainfall forecasts, among other alternatives. This can potentially restrict environmental flows to periods where the probability of tank overflow is high and the impacts to rainwater yield would consequently be limited. Unfortunately, the archives of rainfall forecasts are limited in duration and historic predictions lack the skill of current forecast techniques. These deficiencies are problematic for long-term assessment that incorporates recent advances in forecast skill. Consequently, a method to supplement forecast archives needs to be investigated.

Forecasts of stream flow or rainfall over various horizons are commonly used in conjunction with other indicators to operate large scale reservoirs (Chiew *et al.* 2003; Collischonn *et al.* 2007; Hejazi *et al.* 2008; Zhao & Davison 2009; Lima & Lall 2010; Zhao *et al.* 2011). In the proposed research the feasibility of applying these operating practices to adaptive rainwater systems will be examined.

Stream flow forecasts have low relevance to adaptive rainwater systems as roof hydrology is comparatively simple; therefore, only rainfall forecasts will be considered. Forecast methods are extensive and often complex. A good summary of current atmospheric and oceanic coupled models is reported by Kumar & Krishnamurti (2012). Details of applying the Madden-Julian Oscillation and Predictive Ocean Atmospheric Model for Australia is reported by Marshall *et al.* (2011).

In Australia, short-term daily rainfall forecasts for horizons of one to eight days are issued several times a day at grid locations of 0.5 degrees longitude and latitude by the Australian Bureau of Meteorology (BoM 2012e). Forecasts include estimated rainfall depths and probability of rainfall at various depths between 1 and 100 mm. These forecasts are used in conjunction with other systems to produce general weather forecasts (BoM 2012c).

In applying forecasts, consideration should be given to their accuracy, which may be measured by generic goodness of fit statistics including the coefficient of determination (Xiong *et al.* 2001) or mean squared error of the estimated and observed values. Other statistics discovered in the literature include the mean, standard deviation, correlation coefficient, skewness, coefficient of variation, Pearson's correlation, bias, root mean square error and mean absolute error (Toth *et al.* 2000; Valverde Ramírez *et al.* 2005; Ghile & Schulze 2009). Specific forecast skill metrics are reported by Tartaglione (2010) which include the true skill score (Hanssen & Kuipers 1965) frequency bias and Gilbert skill score, which is also widely known as the equitable threat score (Gandin & Murphy 1992). Similarly, Berenguer *et al.* (2011) together with Hamill & Juras (2006) report skill metrics based on contingency conditions (Stanski *et al.* 1989) which include probability of detection, false alarm ratio, critical success index, conditional mean absolute error, Brier score (Brier 1950) and relative operating characteristic skill score (Mason 1982; Stanski *et al.* 1989; Harvey & Hammond 1992). Generally, forecast accuracy reduces as the lead time or horizon increases (Berenguer *et al.* 2011; Cai *et al.* 2011), also accuracy initially increases and then may reduce as the daily mean accumulation increases, as demonstrated by the results of this chapter.

In order to obtain a comprehensive understanding of the performance of forecast dependent systems, it may be necessary to undertake a long-term analysis which includes several oscillations of large scale weather systems and associated periods of flood and drought. Archives of the El Niño southern oscillation index, measured by surface sea temperature (BoM 2012f) or coral oxygen isotopes (Zinke *et al.* 2004), show a typical periodicity of two to five years. However, forecast accuracy is not static and over this period there could be notable improvements to forecast models and/or input data. Furthermore, looking forward, it is reasonable to presume our forecast skill will increase. Therefore, long-term assessment of the performance of forecast dependent systems should be founded on the accuracy of current forecasting techniques and this would preclude the use of historic rainfall predictions with diminished skill. Thus, a maximum period of 5 years is recommended for application of forecast archives and this is less than a desirable simulation period.

Moreover, in some locations the duration of rainfall prediction archives may be limited, such as national weather prediction services in Germany (Kneis *et al.* 2012) or developing countries. Therefore, in the absence of a suitable duration of rainfall predictions, it is recommended to synthetically supplement predictions to facilitate a long-term analysis.

Many methods can be used to supplement rainfall forecast archives with synthetic data. Artificial neural networks are widely used to generate synthetic data and are suitable for generating forecasts of streamflow or rainfall (Coulibaly *et al.* 2000; Valverde Ramírez *et al.* 2005; Goswami & O'Connor 2007; Wu *et al.* 2010; Wu & Chau 2011). Alternatively, Tartaglione (2010) introduces two parametric models to generate synthetic rainfall forecasts based on a Gaussian distributions and Monte Carlo method. Tartaglione (2010) applies these models to assess the sensitivity of forecast skill metrics.

The approach of supplementing rainfall forecast archives has received very little attention in the literature. Therefore, a review of current methods is needed and will be conducted in this chapter. Thus, this chapter aims to examine methods for supplementing archives of daily rainfall forecasts with synthetic predictions that are statistically equivalent to the accuracy of current rainfall forecast techniques.

Assessment will be limited to forecasts with time horizons within eight days, as this horizon is commonly used and data is readily available. This aim will be achieved by combining historic observations of daily rainfall with the error behaviour of current rainfall forecast techniques. Thus, a long-term time-series of daily rainfall forecasts can be created, which will facilitate long-term simulation and assessment of adaptive rainwater systems and other forecast dependent systems.

7.2 Methodology

The research methodology follows three phases comprising: (1) using a hindcast approach, determine the accuracy of daily rainfall forecasts for Australian capital cities and for various time horizons, daily mean periods and performance metrics; (2) establish and calibrate models for supplementing archives of daily rainfall predictions with synthetic predictions based on the hindcast accuracy discovered; and (3) verify these models using independent rainfall forecasts.

7.2.1 Accuracy of rainfall forecasts

In Australia, rainfall forecasts issued with general weather alerts are more accurate than gridded numerical forecasts, as they include additional consideration of local conditions. Presently with general weather forecasts, for all time horizons but the current day, rainfall is described, such as 'A few showers', which is problematic for quantifying accuracy. Therefore, gridded numerical forecasts were adopted and it is acknowledged this data may not represent the true accuracy of forecasts issued.

Rainfall forecasts for 2008 till 2010 were derived from the gridded archives at weather stations in Australian capital cities (Table 7-1). These sites represent the urban spread and rainfall zones of Australia, with few exceptions (Fig. 7-1).

Table 7-1 Pluviograph statistics for adopted weather stations

Location (state or territory)	Station ID	Pluviograph records	Missing records	Ave. Ann. rainfall	Longitude	Latitude
Adelaide (SA)	23090	12/02/1977 - 18/11/2011	5.9%	496	138.62°E	34.92°S
Brisbane (Qld.)	40913	04/01/2000 - 18/11/2011	13.0%	837	153.04°E	27.48°S
Canberra (ACT)	70014	27/12/1937 - 18/11/2011	14.5%	488	149.20°E	35.30°S
Darwin (NT)	14015	16/09/1953 - 18/11/2011	8.5%	1564	130.89°E	12.42°S
Hobart (Tas.)	94029	30/04/1911 - 18/11/2011	7.9%	574	147.33°E	42.89°S
Melbourne (Vic.)	86282	30/06/1970 - 18/11/2011	11.1%	470	144.83°E	37.67°S
Perth (WA)	09021	03/01/1961 - 18/11/2011	7.4%	678	115.98°E	31.93°S
Sydney (NSW)	66062	03/01/1913 - 18/11/2011	6.1%	1119	151.20°E	33.86°S

Fig. 7-1 Study locations and rainfall zones of Australia. Adapted from (BoM 2009)

The resolution of gridded forecasts increased midway through the archives from 1.0 to 0.5 degrees longitude and latitude. To remain consistent throughout the assessment, the coarser resolution of one degree was adopted and it is acknowledged the higher resolution may achieve higher forecast accuracy. Bilinear interpolation was applied to downscale the gridded data to the pluviograph observation site.

The daily rainfall forecasts at the pluviograph station F_{plv} (mm/d) was determined using the longitudinal difference between the station and the rainfall forecast grid points west Δx $(°E)$, the latitudinal difference between the station and rainfall forecast grid points south Δy $(°S)$ and the gridded forecasts at surrounding points A to D (Fig. 7-2); and is determined with (7-1).

$$F_{plv} = [1 - \Delta y \quad \Delta y] \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} 1 - \Delta x \\ \Delta x \end{bmatrix} \qquad \textbf{(7-1)}$$

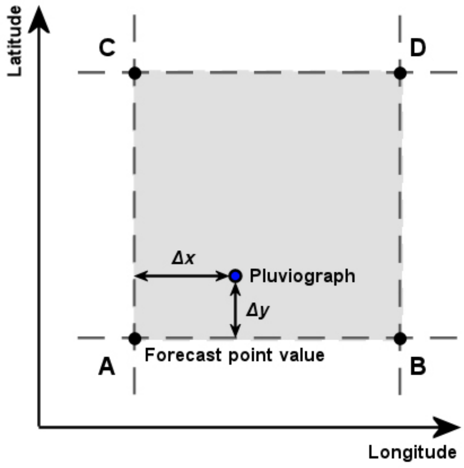


Fig. 7-2 Bilinear interpolation of gridded rainfall forecasts down to pluviograph stations

It is acknowledged that the methodology may have been improved by adopting either the nearest neighbour method or an average observation taken from a cluster of pluviograph sites surrounding one prediction grid point. These alternatives should be investigated in further research.

As previously mentioned, the accuracy of forecast techniques can vary with time horizon and the accumulation period. Several scenarios were examined including single daily forecasts and accumulated means up to eight days, together with horizons up to four days. A forecast horizon of two days was adopted for adaptive rainwater systems. This is based on balancing the accuracy associated with shorter horizons with the desired sustained environmental flow that a longer horizon would facilitate.

Five statistics were used to examine the accuracy of rainfall forecasts, which include: (1) Gilbert skill score GSS which is also commonly referred to as the equitable threat score and is reported to be superior to other forecast skill statistics (Tartaglione 2010); (2) Coefficient of determination R^2, which is widely used and understood, and it is the square of Pearson's correlation; (3) Mean square error MSE, which is commonly used to report the performance of neural networks; (4) Ratio of mean values Rmu, which is introduced in this chapter as the mean prediction divided by mean observation and demonstrates whether the forecast is generally under- or over-estimated; and (5) Ratio of skewness Rsk, as forecast data are not typically normally distributed. The ratio of forecast to observation skewness is used as skewness varies between the period of long-term assessment and the forecast archives.

GSS is based on tallying dichotomous outcomes. In this case, there are four possible outcomes, hit, miss, false alarm and correct negative (Table 7-2). GSS is determined with (7-2), where the number of random hits expected due to chance e is calculated with (7-3) and the four outcomes are tallied from the contingency conditions (Table 7-2).

Table 7-2 Dichotomous forecast outcomes

		Observation	
		Yes	**No**
Prediction	**Yes**	Hit (H)	False alarm (FA)
	No	Miss (MI)	Correct negative (CN)

$$GSS = \frac{H - e}{H + FA + MI - e} \quad \textbf{(7-2)}$$

$$e = \frac{(H + FA)(H + MI)}{H + FA + MI + CN} \quad \textbf{(7-3)}$$

A mean daily threshold of 0.5 mm/d (Tartaglione 2010) was used to determine the dichotomous forecasts and observations. Missing values in pluviograph records (Table 7-1) and archives of rainfall predictions (3.6%) were removed from the analysis to limit bias.

Hamill & Juras (2006) investigate the effects of varying climatology on prediction skill and report skill may be unexpectedly high if climatological event frequencies vary within the assessment period. Therefore, sites with high rainfall seasonality may score artificially high in hindcasts if rainfall time-series data are mistakenly assumed to be homogeneous, as the traditional form of GSS does. To overcome this limitation, it is recommended to determine GSS using sub-samples which have high and low event frequencies or greater fractionation. Sub-samples were apparent in capital cities with seasonally dominant rainfall (Fig. 7-3).

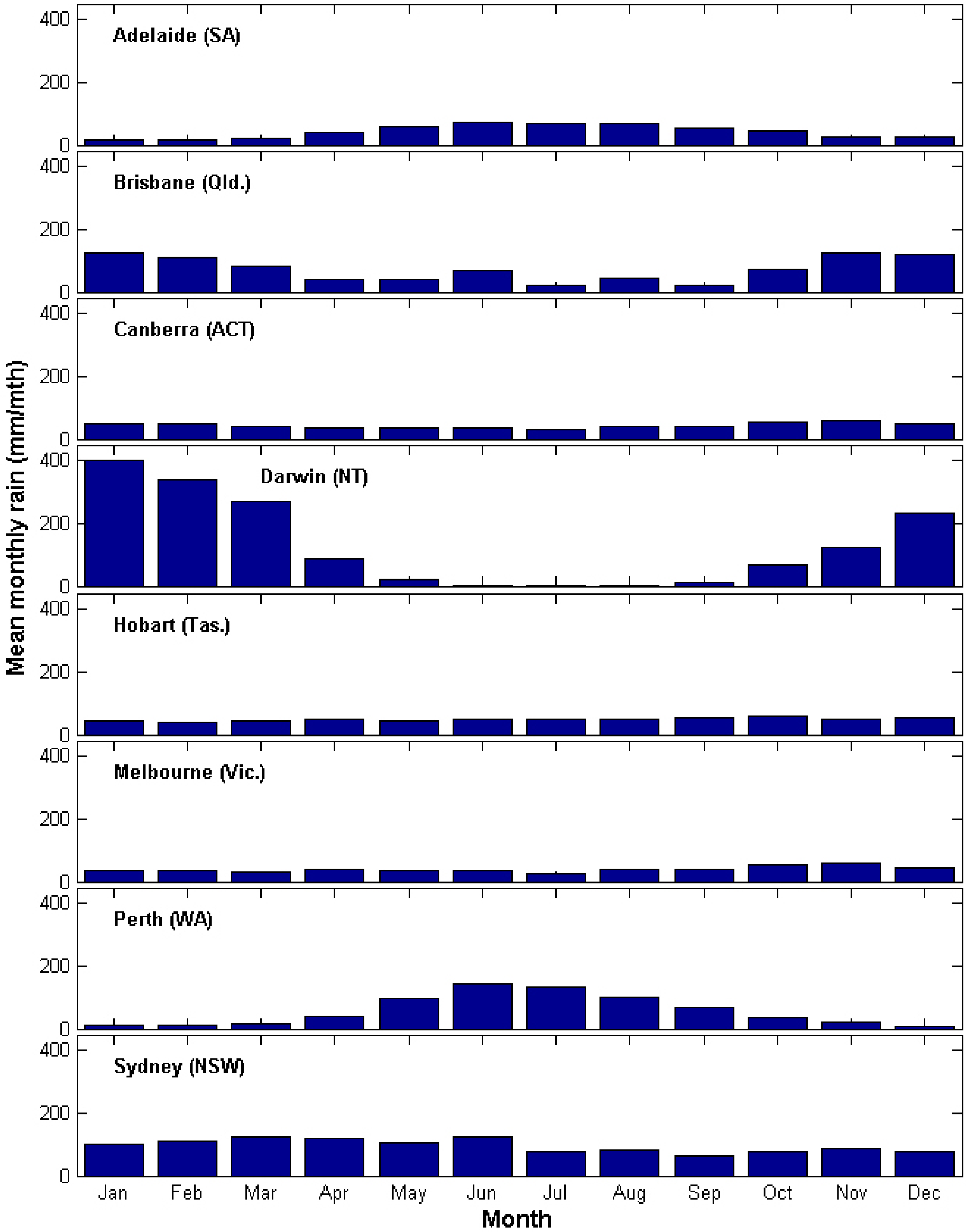


Fig. 7-3 Mean monthly rainfall for capital cities of Australia showing cities with seasonal variation

A contingency condition for detecting the dry sub-sample was established where mean monthly rain days were below 1/36 of mean annual rain days; and otherwise is the high frequency sub-sample. Also, rain days were defined as an observation of at least 0.5 mm/d. In Darwin, where rainfall is dominant in summer, the high frequency wet sub-sample period is from October to April and in Perth, where rainfall is dominant in winter, this period is March to November.

To incorporate sub-samples into GSS, the mean of sub-samples is weighted by their annual fraction and is determined with (7-4), where mths is the number of months in each sub-sample and subscripts h and l denote high and low frequency sub-samples, respectively.

$$\overline{GSS} = \frac{\mathrm{mths}_h}{12} GSS_h + \frac{\mathrm{mths}_l}{12} GSS_l \tag{7-4}$$

7.2.2 Methods to supplement rainfall forecast archives

Four methods were investigated for supplementing archives of rainfall forecasts with synthetic data that is statistically equivalent to the accuracy of current gridded rainfall forecast techniques. Methods comprised (1) artificial neural network (ANN); (2) a three parameter behavioural - Monte Carlo model (BMC); (3) a two parameter Gaussian error model; and (4) a parsimonious percentage error - Monte Carlo model (PMC).

The ANN model (Fig. 7-4) was configured with Lavenberg-Marquardt back-propagation training, random data division, performance assessment by mean squared error, and the default derivative as programmed in MatLab Mathworks software (Beale *et al.* 2011). This configuration is similar to that adopted by others (Coulibaly *et al.* 2000; Taghi Sattari *et al.* 2011). The number of neurons was varied from 5 to 1000. Final results included 100 neurons, as this configuration offered a balance between accuracy and simulation runtime. Twenty simulations per site were performed to provide a distribution of daily synthetic forecasts. Input data was the six day mean rainfall observations and target data was the six day mean gridded rainfall forecasts with a time horizon of two days. Refer to Beale (2011) for a further explanation of ANN networks.

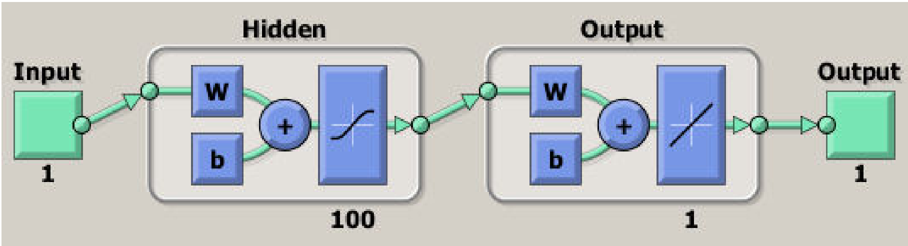


Fig. 7-4 Artificial neural network schematic showing one input series, 100 neurons and one output series.

The three remaining prediction models were calibrated using the five metrics adopted for assessment, (GSS, R^2, MSE, Rmu and Rsk). The BMC model is based on behavioural assessment of rainfall predictions and a Monte Carlo application of the prediction residuals.

Inspection of Sydney rainfall observations and corresponding forecasts (Fig. 7-5) reveals four main points. Firstly, generally, rainfall may be under- or over-predicted, so a mean value adjustment coefficient α (unitless) may be necessary to refine the magnitude of synthetic forecasts. The coefficient may be used to calibrate synthetic forecasts to match the Rmu of gridded forecast archives.

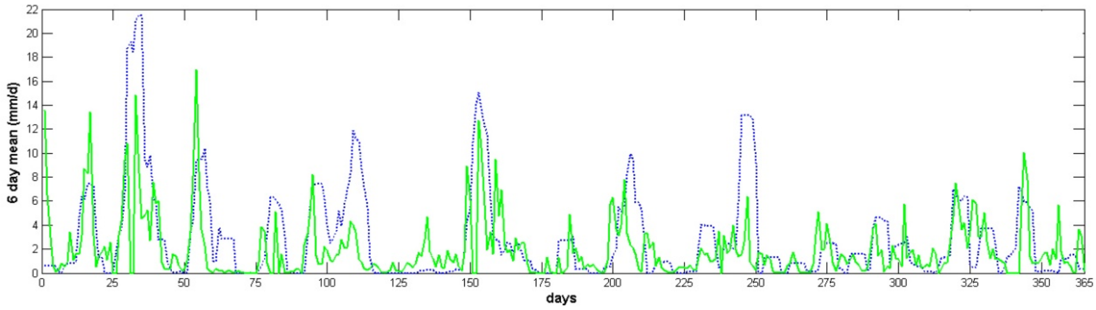


Fig. 7-5 Accumulated six day mean rainfall observation (**blue dots**) and gridded rainfall predictions (**green**) with two day horizon for Sydney in 2008.

Calibration of α followed an iterative approach (7-5) where α_{i+1} is the calibrated coefficient based on the value from the previous iteration α_i , the ratio of mean values from the previous iteration Rmu_i (unitless) and the ratio of mean values from the gridded rainfall forecast archives Rmu_a(unitless).

$$\alpha_{i+1} = \max\big(0, \alpha_i - (Rmu_i - Rmu_a)\big) \tag{7-5}$$

Another point from (Fig. 7-5),unlike days without rain, days with rain can be underestimated (day 110 & 245) or altogether missed (day 60) and would therefore encounter higher errors. Furthermore, over-estimates (day 0, 15 & 55) appear to be larger than false alarms (day 135). Therefore, a forecast residual scalar β (d/mm) may be necessary to scale errors and likewise may be used to calibrate synthetic forecasts by matching the R^2 of gridded rainfall prediction archives.

Similarly, calibration followed an iterative approach (7-6) where β_{i+1} is the calibrated scalar based on the value from the previous iteration β_i and the R^2 of the pervious iteration and the gridded rainfall forecast. A value of zero indicates that forecast errors are not scaled by rainfall observations.

$$\beta_{i+1} = \max\left(0, \beta_i + (R_i^2 - R_a^2)\right) \tag{7-6}$$

Another point from (Fig. 7-5), the dichotomous skill metrics are sensitive to forecasts near the threshold (0.5 mm). Therefore, a forecast skill adjustment constant γ (mm/d) may be necessary. Likewise, the constant may be iteratively calibrated by matching GSS from the rainfall forecast archives (7-7). A small constant may remove some false alarms and larger constant may also remove some hits.

$$\gamma_{i+1} = \max\big(0, \gamma_i + (GSS_i - GSS_a)\big) \tag{7-7}$$

A final observation from (Fig. 7-5), as false alarms can occur, forecast errors cannot be exclusively scaled by rainfall observations. Based on these observations, the mean six day synthetic rainfall forecast from the BMC model $P_{BMC.d}$ (mm/d) can be determined for day d with (7-8), where the linear regression gradient of rainfall observations to gridded rainfall forecast is M (unitless) (see results Fig. 7-6), the six day mean rainfall is r (mm/d) and the six day mean gridded rainfall forecast residuals is ε (mm/d) which is applied using the Monte Carlo method.

$$P_{BMC.d} = \max\big(0, \alpha(M \cdot r(\beta \cdot \varepsilon + 1) + \varepsilon + \gamma)\big) \qquad \textbf{(7-8)}$$

Alternatively, Tartaglione (2010) reports an approach to generate daily synthetic rainfall forecast by applying a Gaussian distribution of errors to rainfall observations. The synthetic rainfall forecasts $P_{Gau.d}$ (mm/d) can be determined with (7-9), where ε_n is the Gaussian distribution of errors with a mean value μ and standard deviation σ, which can be iteratively calibrated with (7-9) and (7-10), respectively.

$$\log_{10}(P_{Gau.d}) = \log_{10}(r) + \varepsilon_n \qquad \textbf{(7-9)}$$

$$\mu_{i+1} = \min(0, \mu_i - (GSS_i - GSS_a)/10) \qquad \textbf{(7-10)}$$

$$\sigma_{i+1} = \max(0, \sigma_i + (MSE_i - MSE_a)/100) \qquad \textbf{(7-11)}$$

Finally, Tartaglione (2010) also reports an approach based on a percentage error and Monte Carlo application PMC. In this case, the synthetic rainfall forecasts $P_{PMC.d}$ (mm/d) can be determined with (7-12) where ω (unitless) is the percentage error with a sign determined by a Monte Carlo approach and iteratively calibrated with (7-13).

$$P_{PMC.d} = \max\big(0, r(\omega + 1)\big) \quad \textbf{(7-12)}$$

$$\omega_{i+1} = \omega_i + (GSS_i - GSS_a) \quad \textbf{(7-13)}$$

7.2.3 Verification of synthetic forecast data

The final year (2011) of the gridded forecast archives was reserved to verify the models. However, as forecasts and rainfall observations are highly varied, this limited period was unable to offer definitive results. Therefore, the two year period of 2010 to 2011 was used for verification and it is acknowledged this is not entirely an independent approach.

Verification is by the GSS metric and is determined by comparing three scenarios: (1) the baseline, which is the hindcasts of gridded predictions for the years 2008 to 2010; (2) all synthetic forecasts using all available pluviograph observations; and (3) the partially independent period of gridded forecasts from 2010 to 2011.

7.3 Results and discussion

Results are presented following the three phases of the methodology.

7.3.1 Accuracy of gridded rainfall forecast archives

By coefficient of determination, the forecast skill appears to be only moderate (Fig. 7-6) with a range of $0.39 \leq R^2 \leq 0.61$. However, this is a comparison of spatially averaged forecast with single point sources of observations. Assessment of accuracy with observations at grid points in the forecast archive is expected to yield better results, as errors from downscaling are removed. Furthermore and as previously mentioned, an observation mean taken from a cluster of pluviograph stations surrounding one grid point is also expected to yield greater forecast accuracy. The most accurate results appear to be in locations where rainfall is seasonally dominant such as Darwin or Perth. However as previously mentioned, these sites have artificially inflated skill due to a large number of low values in the time-series data.

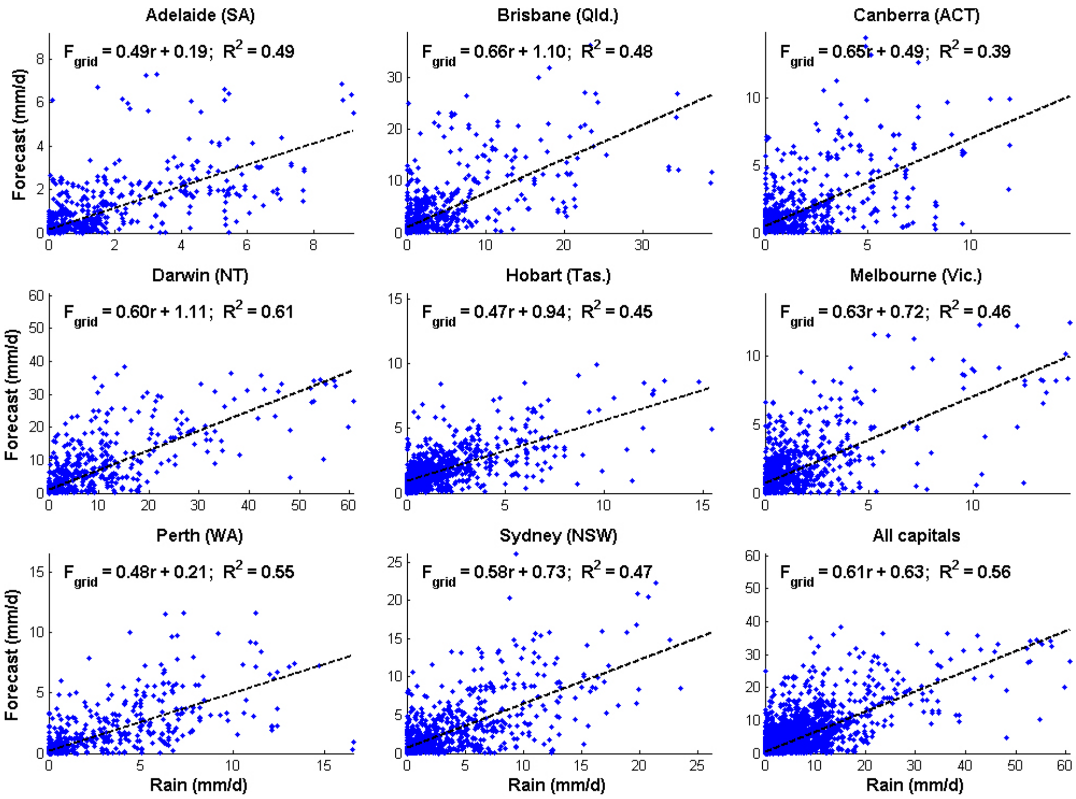


Fig. 7-6 Mean six day rainfall observation (rain) and gridded rainfall forecasts with 2 day horizon for capital cities of Australia. Note that axis scales vary.

A GSS value of one is a perfect forecast and a value of zero or less is no better than chance. With minor exceptions, maximum and minimum skill is similar for all locations and consistently relates to forecast horizon (Fig. 7-7). However, in some locations the peak skill is not discovered within the eight day accumulation period or it occurs surprisingly early. Therefore by this metric and with a 0.5 mm/d contingency threshold, an optimum scenario does not exist in which peak skill is obtained in all rainfall zones. Sites where a peak skill is apparent, such as Hobart and Sydney, are all within a uniform rainfall zone (Fig. 7-1 and Fig. 7-3). At these locations the number of random hits expected due to chance increases significantly over the accumulation period (Table 7-3). This corresponds to a reduction in the occurrence of correct negatives. However, in Melbourne the change in dichotomous tallies over the accumulation period is similar but a peak skill is not observed. Therefore, there are further relationships to be considered before a complete explanation can be reached and this is the topic of ongoing research.

It is acknowledged the trigger for responding to rainfall forecasts may not occur at the threshold studied, so thresholds from 0 to 5 mm/d were examined (Table 7-4 and Appendix A). No overall improvement to peak GSS values was found. Therefore, the 0.5 mm/d threshold was adopted for calibrating the synthetic forecast data.

Additional metrics of MSE, R^2, Rmu and Rsk were also studied (Appendix A) which revealed the GSS was the most suitable metric for this analysis.

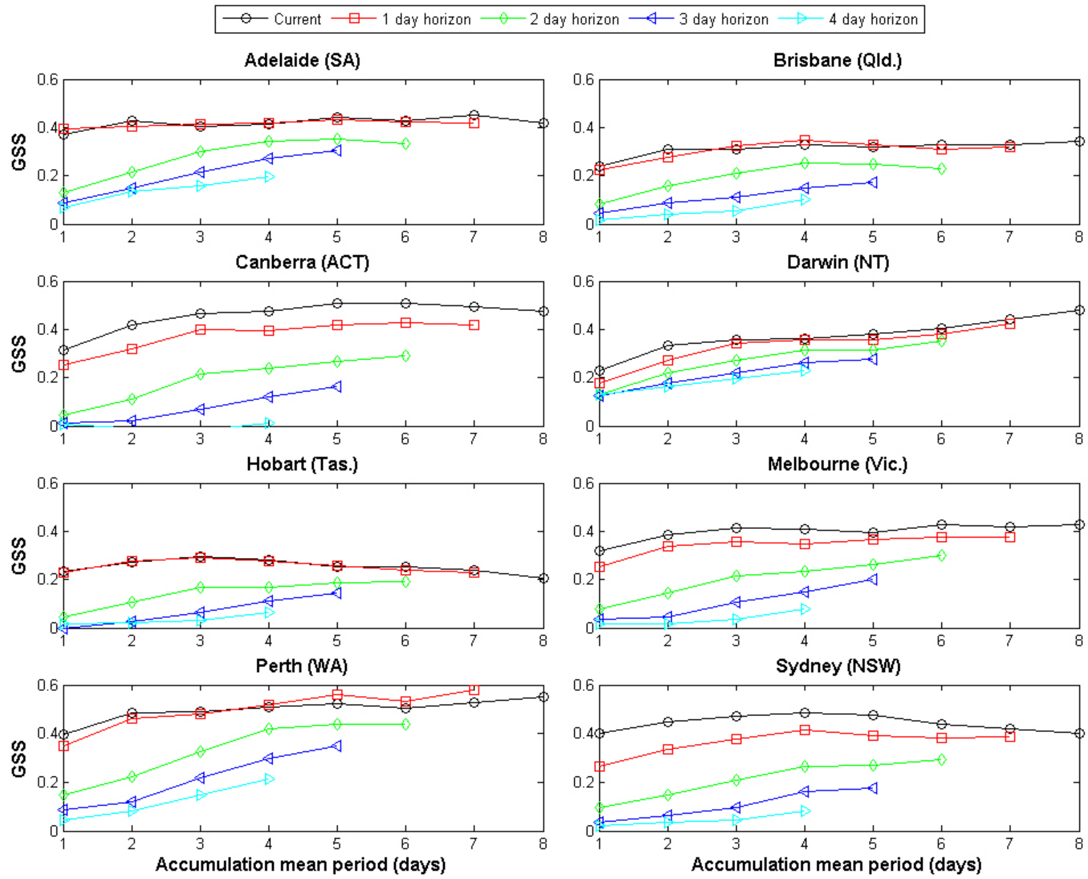


Fig. 7-7 Gilbert skill scores (GSS) for gridded forecasts with various time horizons and daily mean accumulation periods. Note that the skill reduces for large mean accumulation periods in Hobart and Sydney.

Table 7-3 Change in dichotomous tallies over accumulation period for current day predictions and with 0.5 mm/d threshold

Site	Δ Hit (H)	Δ False alarm (FA)	Δ Miss (MI)	Δ Correct negative (CN)	Δ Random hits by chance (e)
Adelaide	169	4	18	-191	93
Brisbane	301	-99	-11	-191	203
Canberra	311	-52	10	-269	200
Darwin	196	-141	21	-76	109
Hobart	397	-34	-30	**-333**	**412**
Melbourne	361	-21	-24	-316	300
Perth	203	-30	10	-183	102
Sydney	385	-80	38	**-343**	**396**

Note that bold values are demonstrate the distinction for discovering peak skill within the 8 day accumulation period

Table 7-4 Change is Gilbert Skill Score peaks for contingency thresholds

Contingency threshold (mm/d)	Peaks found additional to 0.5 case	Higher skill	Lower skill	Earlier peak	Double peak
0.25	Adelaide	Brisbane	Canberra Sydney	Sydney	-
0.50	**Hobart Sydney**	**-**	**-**	**-**	**-**
0.75	Canberra Melbourne	-	-	Hobart Sydney	-
2.5	Adelaide Brisbane Perth	Brisbane Hobart Sydney	-	Perth	Canberra
5.0	Canberra Darwin	Brisbane Hobart Sydney	Adelaide Canberra Darwin Perth	Adelaide Perth	Melbourne Sydney

7.3.2 Supplementing daily forecast archives

Final calibration of parameters for all synthetic prediction models is shown (Table 7-5).

Table 7-5 Calibrated parameters for rainfall prediction models

Model	**Behavioural - Monte Carlo (BMC)**			**Gaussian**	**PMC**
Parameter / Site	$\boldsymbol{\alpha}$ (-)	$\boldsymbol{\beta}$ (d/mm)	$\boldsymbol{\gamma}$ (mm/d)	$\boldsymbol{\mu \pm \sigma}$ (mm/d)	$\boldsymbol{\omega}$ (-)
Initial condition	*0*	*0*	*0*	*-0.50 ± 0.50*	*0*
Adelaide	1.88	0.43	0.40	-0.59 ± 0.40	0.88
Brisbane	1.79	0.02	2.05	-1.00 ± 0.65	1.17
Canberra	1.59	0.41	0.92	-0.66 ± 0.42	0.93
Darwin	1.13	0.02	0	-1.10 ± 0.64	1.30
Hobart	2.19	0.55	0.99	-0.75 ± 0.50	1.37
Melbourne	1.06	0.33	0	-0.58 ± 0.45	0.91
Perth	1.29	0.49	0	-0.58 ± 0.41	0.85
Sydney	1.13	0.30	0	-0.85 ± 0.49	0.98

Comparison of the GSS of all synthetic forecast models to the gridded rainfall forecasts in all capital cities is shown with boxplots to demonstrate the distribution of model predictions (Fig. 7-8). The parametric models provide superior results to the ANN model, which is not surprising as the parameters γ, μ and ω in the BMC, Gaussian and PMC models are calibrated by GSS. With the ANN model, all locations have higher skill scores, which is not desirable. This suggests the ANN model follows rainfall observations too closely and is unable to identify sufficient errors from the gridded forecast residuals provided during model training. While forecast skill is a widely adopted metric for accuracy assessment, other metrics are considered in the results and discussion following.

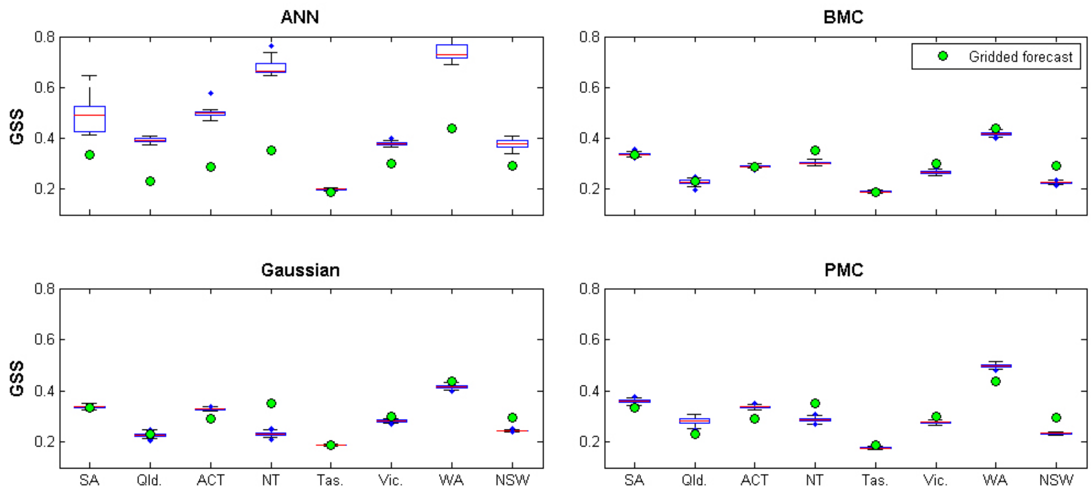


Fig. 7-8 Boxplots of Gilbert skill score GSS for all synthetic forecast models and gridded forecasts. Note that the elevated skill for the ANN model is undesirable.

Comparisons of the coefficient of determination of all synthetic forecast models (Fig. 7-9) demonstrated the BMC model is superior, as β is calibrated by this metric. The PMC model also produces reasonable results, whereas the ANN and Gaussian models are generally too low.

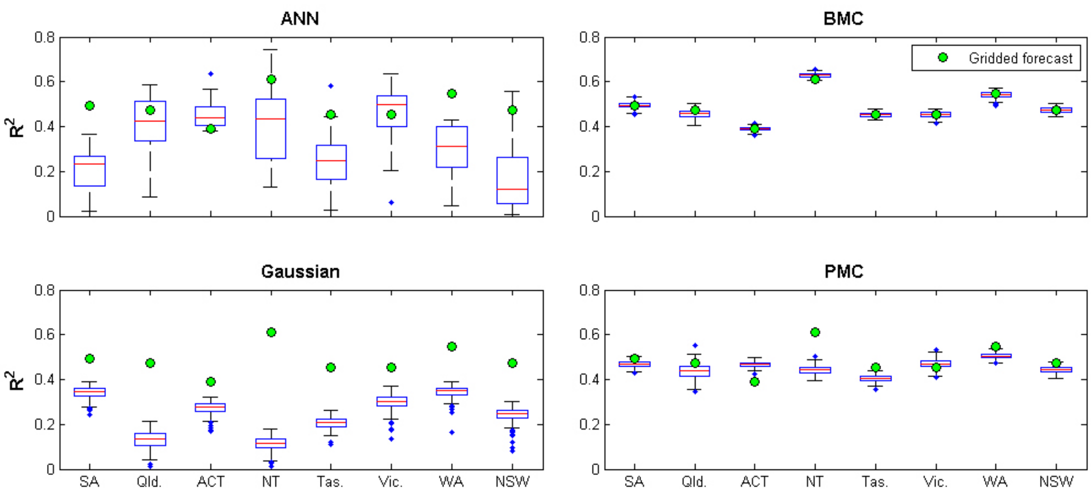


Fig. 7-9 Boxplots of coefficient of determination (R^2) for all synthetic models and gridded forecasts. Note that the low correlations for the Gaussian model are undesirable; and ANN model instability is evident by the broad distribution.

Comparisons of the mean square error of all synthetic forecast models (Fig. 7-10) demonstrate instability of the ANN model. Also, the Gaussian model is superior, as

σ is calibrated by this metric. The BMC and PMC models provide reasonable results, although neither are calibrated using this metric.

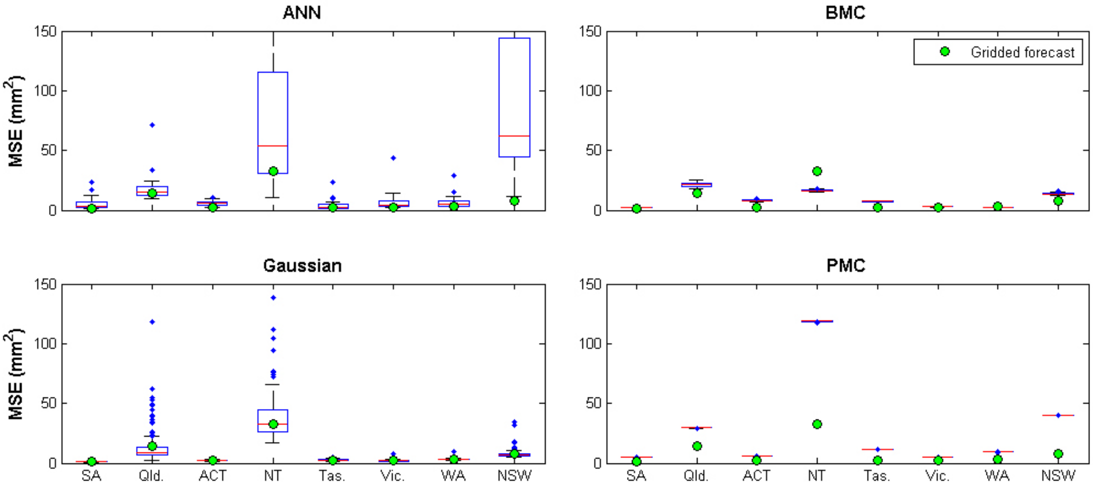


Fig. 7-10 Boxplots of mean square error (MSE) for all synthetic models and gridded forecasts. Note that the ANN model instability is evident in the broad distribution in some locations.

Comparisons of the ratio of mean values (Fig. 7-11) demonstrates the BMC model provides superior results, as α is calibrated by this metric. The ANN and PMC models provide reasonable results, whereas the Gaussian model shows poor results.

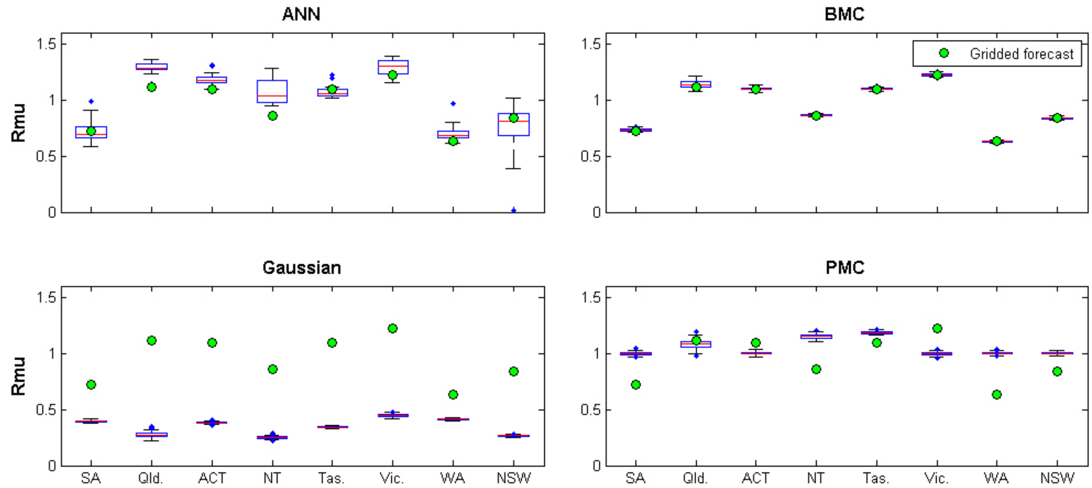


Fig. 7-11 Boxplots of ratio of mean values (Rmu) for all synthetic models and gridded forecasts. Note that the low ratios for Gaussian model are undesirable.

Comparisons of the ratio of skewness (Fig. 7-12) demonstrate superior results are achieved with the ANN and PMC model, reasonable results are achieved with the BMC model and poor results are achieved by the Gaussian model.

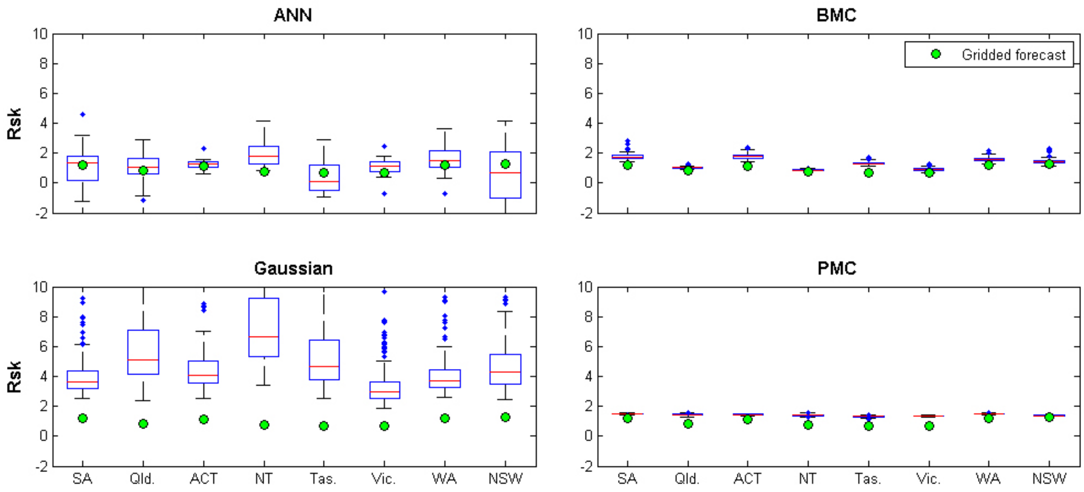


Fig. 7-12 Boxplots of ratio of skewness (Rsk) for all synthetic models and gridded forecasts. Note that the elevated skewness for Gaussian model is undesirable.

Overall, from these metrics and calibrating to gridded rainfall forecasts for Australian capital cities, the BMC model is superior. Furthermore, the parametric models were computationally economical to operate (1600 time-series of forecasts in one minute), in comparison to the ANN model (160 time-series predictions in twelve hours). Due to the economy of the parametric models, the distribution of daily rainfall forecasts was increased to 200 per site.

Time series of synthetic rainfall forecasts (Fig. 7-13) demonstrate the capacity to emulate the behaviour of current forecast techniques by comparison with gridded rainfall forecast archives. Emulation of behaviour includes overestimation, underestimations, misses and false alarms. The BMC synthetic forecasts perform well in many locations including those with dominate rainfall seasons such as Darwin, where a low occurrence of false alarms is observed during winter, and similarly for Perth during summer. One discrepancy is the burst nature of the Hobart BMC synthetic forecasts, and to a lesser extent in other locations. This behaviour does not represent the gridded rainfall forecast archives particularly well. This may be attributed to the high α value, but not exclusively, as sites with moderate values do not consistently display this behaviour. Therefore, further investigation of alternate statistics to calibrate the α parameter are recommended to improve the BMC model.

Results from ANN, Gaussian and PMC synthetic forecast models (Appendix B) show the ANN model follows rainfall observations too closely which provides a narrow distribution of synthetic forecasts and limited errors, as shown by high GSS values (Fig. 7-8). Also, in some locations minimum forecasts were greater than zero and very close to the contingency threshold. This could potentially provide poor results for this model.

The Gaussian model contains lots of excessive forecasts. This is evident by the low coefficient of determination (Fig. 7-9). However, the model also generates few false alarms, which is uncharacteristic of rainfall forecast archives. This explains why reasonable GSS values are shown (Fig. 7-8) and why more than one metric should be considered in hindcasts of rainfall forecasts.

Finally, the PMC model is very noisy with many peaks. These erratic forecasts are also uncharacteristic. This shortcoming was not evident in any of the metrics studied and suggests a serial correlation metric may provide further information and opportunities to calibrate the models.

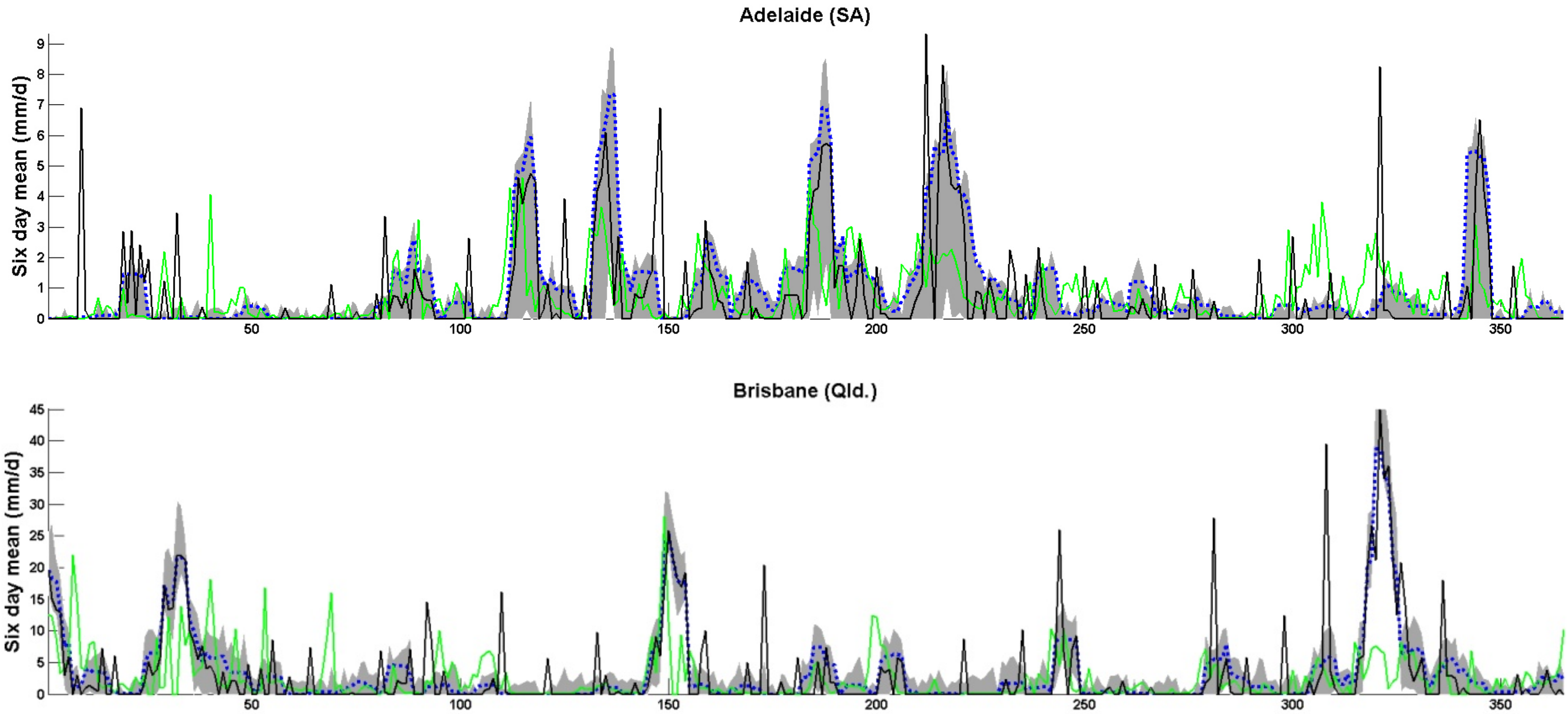
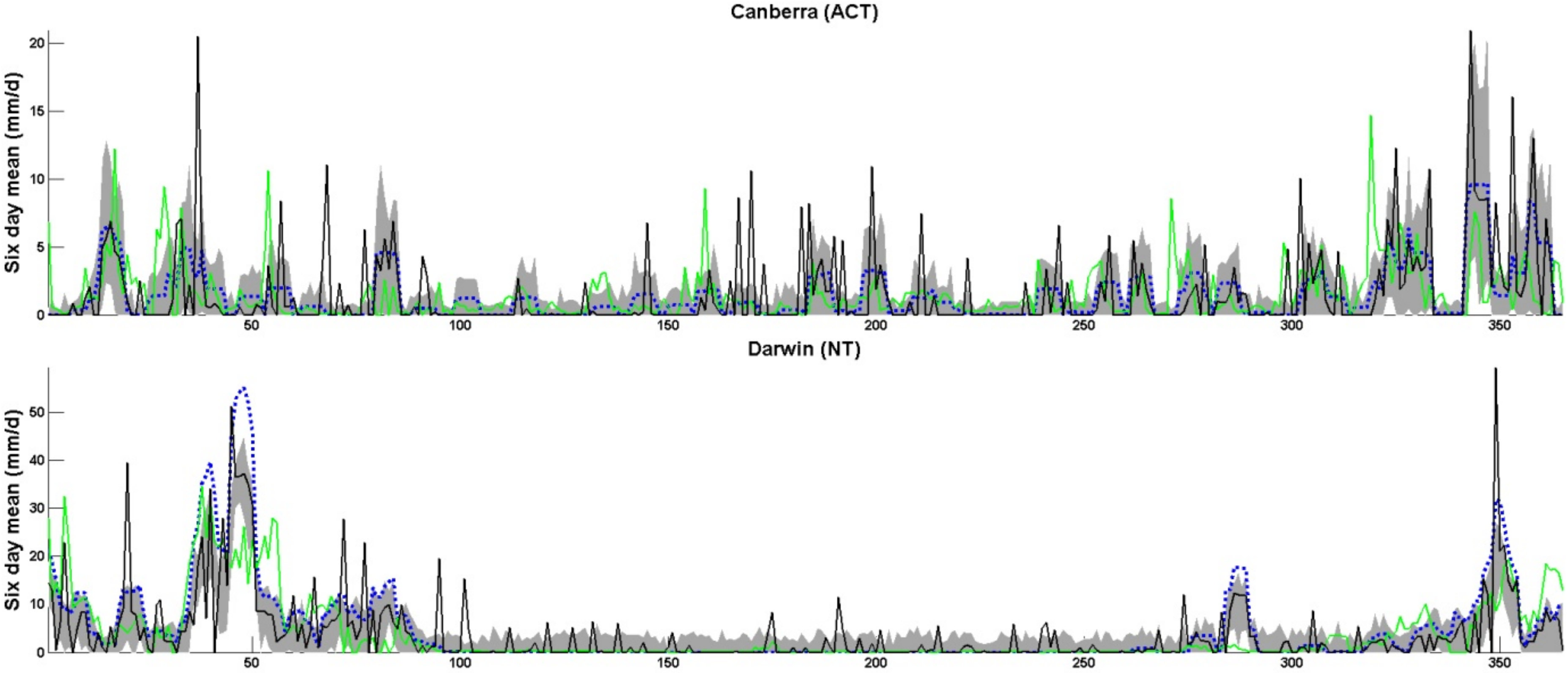


Fig. 7-13 Prediction distribution between 0.1 and 0.9 quantile (**gray band**), six day mean rainfall observation (**blue dots**), six day mean and two day horizon gridded rainfall prediction (**green**) and sample BMC synthetic forecast in 2008 (**black**). Note that for clarity, the y-axis scales varies and figure continues ...



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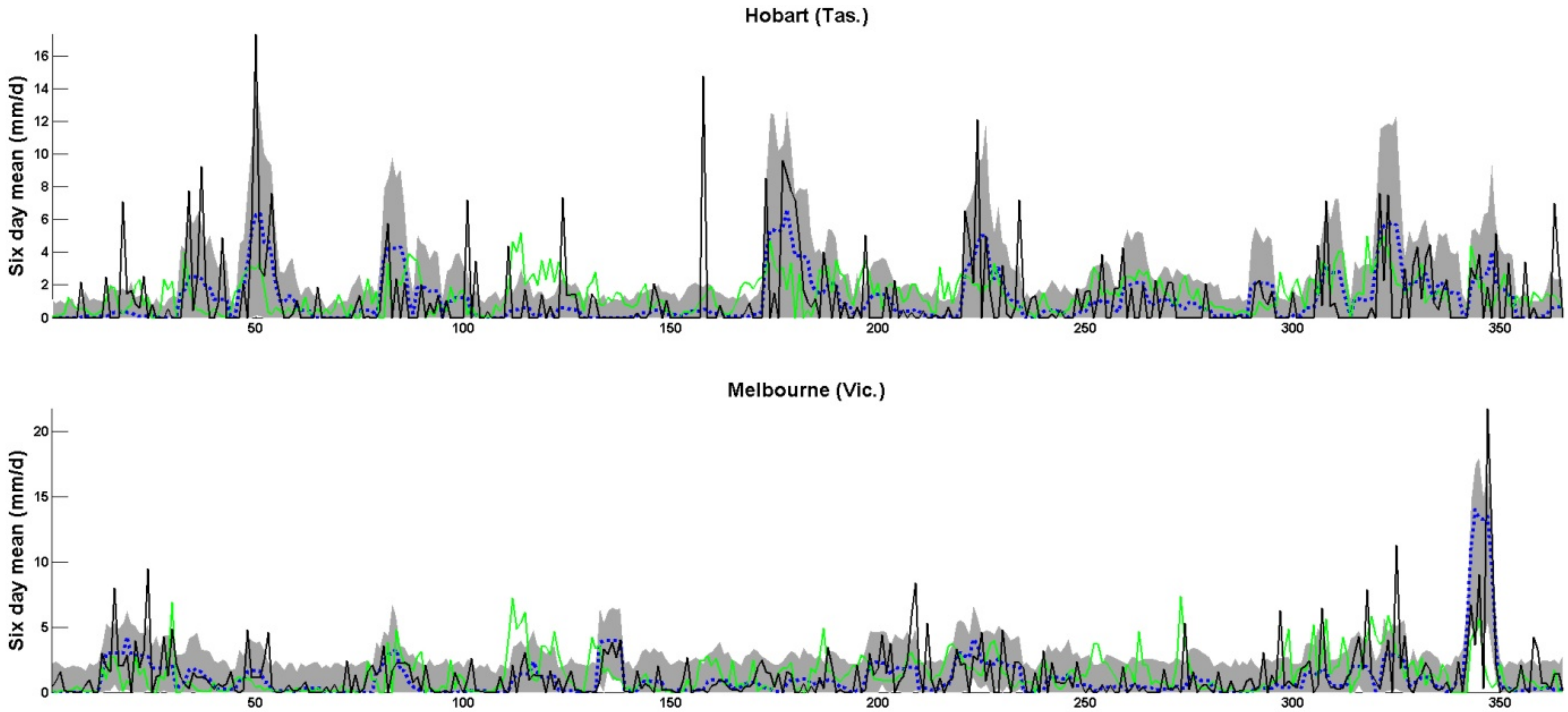

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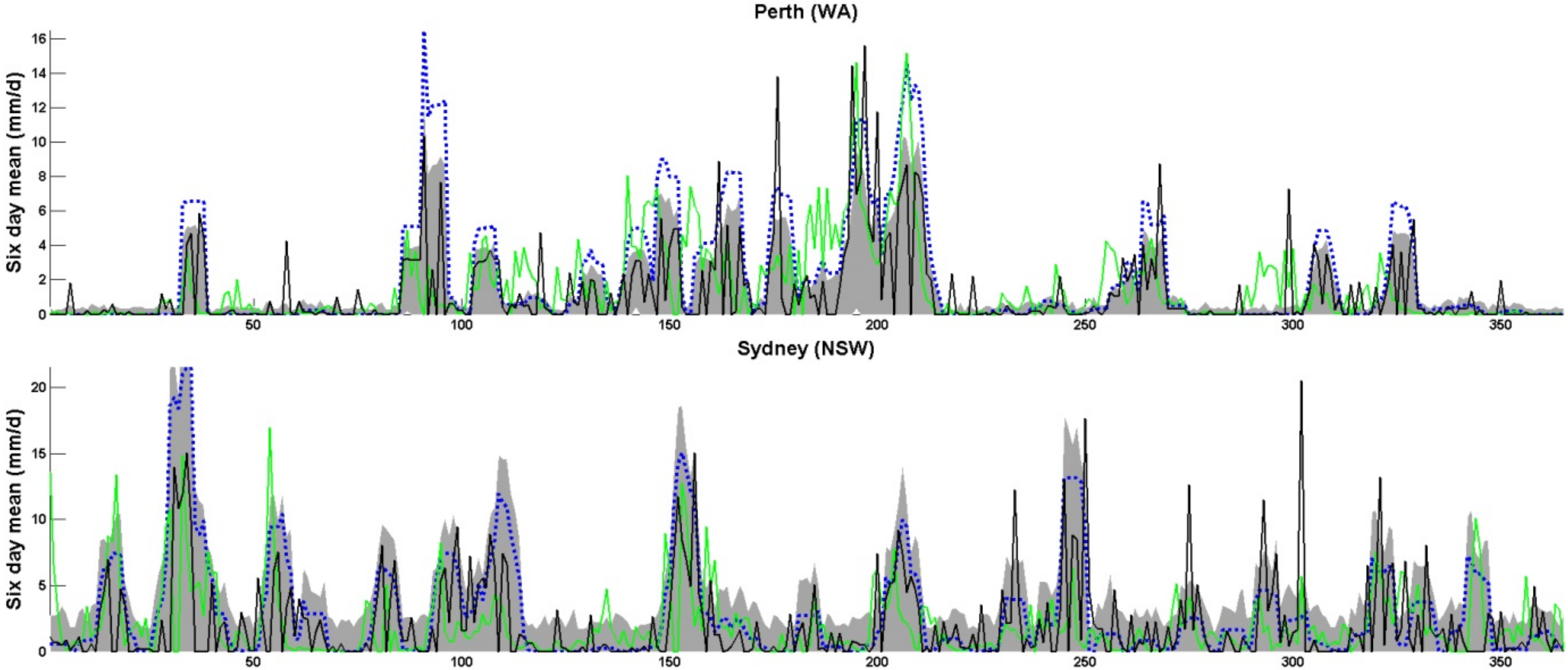


Fig. 7-13 complete.

7.3.3 Verification of synthetic forecasts

Verification of the synthetic prediction models was performed using the 2008-2010 gridded rainfall predictions as a baseline and 2010-2011 gridded rainfall predictions as verification limit (Fig. 7-14). Performance is measured by GSS and the departures from the baseline are shown. The accuracy of synthetic models is annotated as 'Synthetic forecast departures'. Generally the departures of the parametric models are within the verification departure, especially the BMC model. This demonstrates these models are suitably verified. The ANN model showed excessive departure in some locations. The departure of the gridded forecasts for 2010-2011 demonstrates how the gridded forecast accuracy can change over time. For most locations the departure from the baseline is reasonably small. However Adelaide is an obvious exception.

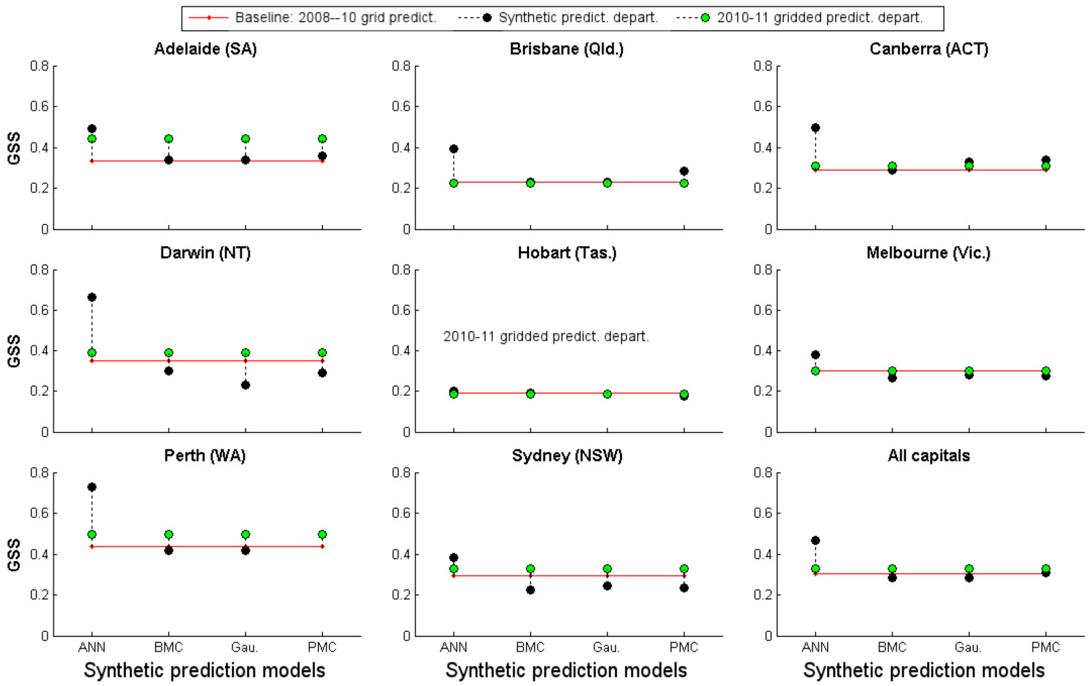


Fig. 7-14 Stem plots of GSS departures from for all synthetic prediction models in all cities from the baseline of the gridded predictions for 2008-2010. Note that the departure of the BMC model is small and within the magnitude of the 2010-2011 gridded prediction departures.

7.4 Summary of supplementing rainfall forecast archives

Using a hindcast approach, the accuracy of daily gridded rainfall forecasts over the years 2008 to 2011 was studied for capital cities in Australia. Examination included horizons up four days and mean accumulations up to eight days. Generally, the best results occur with an eight day mean and for the forecast of the current day. However, some locations showed a reduction in accuracy beyond an accumulation of three to five days. By various metrics, rainfall forecasts appear to have only moderate skill. However, the approach compared a spatially averaged forecast with a small sample of rainfall point observations. Alternatives have been suggested which may improve this assessment and demonstrate greater accuracy.

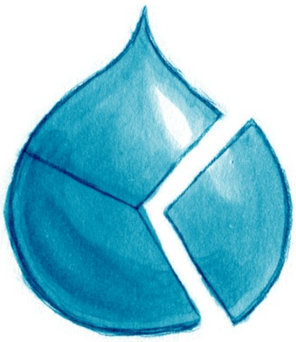
Four methods were examined to supplement daily archives of rainfall forecasts with synthetic data that is statistically equivalent to the accuracy of current forecast techniques. The accuracy of forecast models was tested using several metrics and overall, the BMC model was shown to be superior. Inspection of rainfall observations and synthetic forecasts for 2008 revealed some improvements could be made to the BMC model to prevent forecast bursts, which is uncharacteristic of current forecast techniques in some locations.

All synthetic forecast models were verified by additional gridded forecast data and sound results were observed for the three parametric models. The ANN model did not perform well during verification.

Therefore, by the methods herein, rainfall forecast archives of limited duration or diminishing accuracy can be supplemented to create long-term time-series of daily rainfall forecasts that are statistically equivalent to the accuracy of current forecast techniques. It is recommended to use the BMC model which was successfully applied to Australian capital cities which represent the diverse rainfall zones throughout Australia. As forecast techniques improve in accuracy, parameter values can be recalibrated following the procedures herein. These results provide an avenue to undertake long-term assessment of adaptive rainwater systems, and other systems dependent on rainfall forecasts.

Chapter 8 Rainwater Tank Performance Examined

Operating rules and dual-duty performance of all tank types is examined for various scenarios in all capital cities. The result demonstrates that conventional rainwater tanks are inferior and the adaptive approaches provide only minor improvement over the leaking tank arrangement.



8.1 Introduction

The core results of the dissertation are presented in this chapter in two phases consisting operating rules for adaptive rainwater tanks; and simulation results and discussion for various modelling scenarios. Modelling was conducted using the full simulation period at each location (Fig. 4-4) which typically incorporates 30 to 90 years of input data comprising six minute rainfall observations, daily maximum temperature observations and supplemented daily rainfall forecasts. The simulation was performed by the model described in Chapter 4 and incorporates the seasonal variation of outdoor water use, as defined in Chapter 5; the environmental benefit of rainwater tanks, as defined in Chapter 6; and supplemented archives of rainfall forecasts following the procedures in Chapter 7.

This chapter tests the first two of three phases presented in the research hypothesis: environmental flows from rainwater tanks will increase their dual-duty performance; and an adaptive approach for environmental releases may provide superior results. Also, results presented will answer additional research questions: (1) to what extent are environmental flows detrimental to rainwater supply; (2) are other allotment-scale WSUD components needed in conjunction with rainwater tanks to achieve restoration of aspects of pre-urban stream hydrology; and (3) to what extent does the dual-duty performance vary over the spectrum of urban residential settings typically found in Australia?

8.2 Operating rules for adaptive rainwater tanks

As discussed in Chapter 4, for a fundamental approach it is recommended that control signals for releasing environmental flows from rainwater tanks be based on rainfall statistics, rainfall forecasts, and/or a combination of both. It has also been acknowledged that there are many other catchment specific factors which influence the occurrence of baseflow, such as topography, land use, soil type, etc.

8.2.1 Historical rainfall statistics as a control signal

Where the control signal is based exclusively on rainfall statistics, the volume of the environmental flow chamber in the rainwater tank was positively correlated to the mean monthly rain day index RDI_m (unitless). RDI_m is the ratio of mean days per month where daily rainfall is above a minimum threshold, which corresponds to rainfall abstraction from vegetation interception. Daily thresholds from 0 to 10 mm were independently trialled for each capital city and a value of 2 mm was found to be a critical threshold for deriving RDI_m. This value is consistent with the lower end of forest canopy intersection measurements (Croton & Norton 2001). This allows the control signal for enabling environmental flow from the tank to be based on rainfall that is likely to infiltrate into the soil. Finally, the monthly percentage of tank storage dedicated to the environmental flow chamber E_m (unitless) can be determined with (8-1) by standardising RDI_m with the extreme monthly rain day frequency of 15, which was also discovered to be consistent among all cities.

$$E_m = min\left(0.9, max\left(0, {}^{RDI_m}\!/_{15}\right)\right) \times 100 \qquad \textbf{(8-1)}$$

Therefore, where the mean monthly frequency of days with rainfall exceeding 2 mm is equal to or greater than 15, the environmental flow chamber will comprise 90% of tank storage. The monthly storage allocation varies by location (Fig. 8-1) which illustrates the seasonality of rainfall frequency.

It is acknowledged that this approach does not capture all mechanisms that drive stream baseflow and it is recommended that practitioners consider other catchment specific drivers.

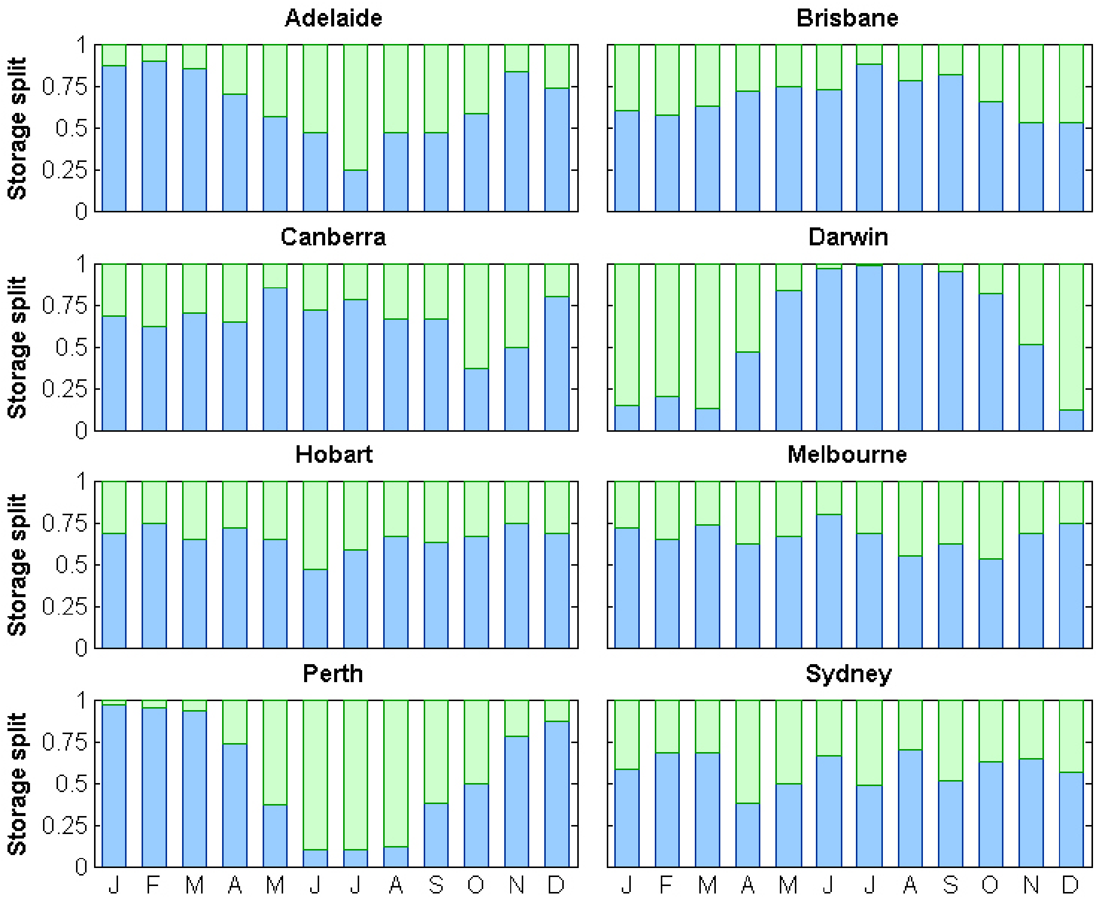


Fig. 8-1 Monthly rainwater storage splits between chambers of environmental flow (**green**) and water supply (**blue**) for adaptive rainwater tanks

In some locations the seasonal variation is rather subtle and the adaptive approach is not expected to be notably superior to the fixed approach of the leaking tank arrangement. In Adelaide, Darwin and Perth there is a notable change in the dual-duty priority of adaptive rainwater tanks between preserving water supply and maximising capacity for environmental flow and runoff interception.

8.2.2 Rainfall forecasts as a control signal

A conundrum exists with the forecast horizon. A balance is sought between the higher accuracy of rainfall forecasts with short horizons (hours) and the necessity for a sustained period of environmental flow (at least days). A two day horizon was established based on the decline in forecast skill at longer horizons, as discussed in Chapter 7. Moreover, this horizon allowed a six day mean accumulation of forecasts out to the maximum eight day horizon in gridded forecast archives. The six day mean is generally more accurate and less erratic than single day forecasts over this horizon. Also, a six day mean allowed larger forecasts to be acted on much earlier.

In the scenario where only the forecast control signal was considered, the daily volume of the environmental flow chamber as a percentage of total storage E_d (unitless) was correlated to the forecast severity. Forecast severity can be determined with (8-2) where F_{6d} is the six day mean forecast rainfall with a two day horizon (mm/d), F_t is the trigger threshold for acting on the forecast (mm/d) and their difference is standardised by the extreme forecast threshold F_e (mm/d).

$$E_d = \begin{cases} min\left(0.9, max\left(0, {(F_{6d} - F_t)}/{F_e}\right)\right) \times 100, & F_r > F_t \\ 0, & \text{otherwise} \end{cases} \qquad \textbf{(8-2)}$$

Trigger and extreme prediction thresholds were calibrated for all capital cities and with few exceptions the best results were obtained using 0.5 mm/d and 3.5 mm/d, respectively. Therefore, with a six day mean prediction of 3.5 mm/d the environmental flow chamber will comprise 90% of tank storage. This could consist of a single forecast of 21 mm/d or higher over the six day period from 25 to 192 hours ahead. A mean forecasts below 0.5 mm/d or less than a single forecast of 3 mm/d would disable environmental flow, and a linear response was established between these limits.

8.2.3 Combined control signal

The basis of the combined approach is to extend the duration of environmental flow from the rainwater tank by potentially releasing flow before the storm commences (forecast signal), during the storm and afterwards (statistical signal). Therefore, with this approach the daily percentage of storage allocated to the environmental flow chamber E_{dc} (unitless) is defined with (8-3).

$$E_{dc} = \max(0.3 \times E_m, E_d) \qquad \textbf{(8-3)}$$

Priority is given to the forecast signal with a fall back condition of a fraction of the statistical signal. This fraction was included to avoid excessive environmental flow.

8.3 Base scenario dual-duty performance

In Chapter 3, a base scenario was established from common or mean parameter values discovered in the literature. This scenario comprises a connected roof area of 150 m^2, average annual rainwater demand of 87 kL/y and tank volume of 5 kL. By an iterative approach of adjusting environmental flow rates and the volume of the environmental flow chamber, the maximum volumetric utility was discovered in all capital cities (Table 8-1). The optimum environmental flow chamber for the leaking tank varied marginally from 40% to 60% (Table 8-1). Flow rates from leaking tanks were often less than the adaptive alternative which should provide a desirable result by extending the duration of sustained environmental flow from leaking tanks (Table 8-2).

With few exceptions, flow rates were not greater than 300 L/day, which provides sustained environmental flow of approximately 5 days, depending on the outdoor rainwater use (Table 8-2). High environmental flow rates (>600 L/day) occur at sites with seasonal rainfall but shorter durations of sustained flow are not anticipated due to higher rainfall frequency in these locations.

Table 8-1 Annual average volumetric utility for base scenario

	VU for tank types				
	Conventional	Leaking	Adaptive		
Cities			Statistics	Forecasts	Combined
Adelaide	0.43	0.60 (45%)[a]	0.60	0.60	0.59
Brisbane	0.43	0.57 (40%)	0.58	0.57	0.58
Canberra	0.46	0.61 (50%)	0.61	0.61	0.61
Darwin	0.26	0.47 (50%)	0.47	0.47	0.47
Hobart	0.47	0.62 (60%)	0.62	0.62	0.62
Melbourne	0.48	0.61 (55%)	0.60	0.61	0.61
Perth	0.34	0.51 (50%)	0.51	0.53	0.53
Sydney	0.42	0.56 (40%)	0.56	0.56	0.57
Mean	*0.41*	*0.57*	*0.57*	*0.57*	*0.57*

[a] Portion of total tank storage allocated to the environmental flow chamber for the leaking tank, which is fixed over time but varies by location and with system design parameters.

Table 8-2 Environmental flow rates for the base scenario (L/day)

	Conventional	Leaking	Adaptive		
Cities			Statistics	Forecasts	Combined
Adelaide	N/A	100	100	300	100
Brisbane	N/A	300	900	600	600
Canberra	N/A	100	300	300	300
Darwin	N/A	900	900	900	900
Hobart	N/A	100	300	300	300
Melbourne	N/A	100	300	300	300
Perth	N/A	100	100	300	300
Sydney	N/A	600	600	600	300

The average annual volumetric utility, or dual-duty performance, was consistently higher for leaking and adaptive tanks (Table 8-1). The national average shows the conventional tank is inferior (0.41) and adapting environmental flows to rainfall statistics and rainfall forecasts offers no noteworthy advantage over a fixed leaking tank (0.57), for the base scenario. Thus, the research hypothesis is valid, so far as environmental flows increase tank dual-duty performance; and invalid, where an adaptive approach to enabling environmental flows failed to achieve superior results.

Leaking and adaptive tanks show similar improvement in volumetric utility over the conventional tank, except for Darwin where greater results occur. Thus from these results, rainwater tanks could be designed to achieve a volumetric utility of 0.5 or higher but this may not be possible in all scenarios.

In all cities, supply independence is marginally reduced for leaking and adaptive tanks (Table 8-3) and there is no overall benefit with the adaptive approach. This minimal reduction (2%) demonstrates that rainwater supply is not excessively sacrificed when environmental flows from rainwater tanks are properly managed. Thus, the first additional research question is answered for the base scenario: *to what extent do environmental flows diminish rainwater supply?*

Table 8-3 Annual average supply independence for base scenario

	***SI* for tank types**				
	Conventional	**Leaking**	**Adaptive**		
Cities			**Statistics**	**Forecasts**	**Combined**
Adelaide	0.23	0.22 (45%)[a]	0.22	0.23	0.23
Brisbane	0.30	0.27 (40%)	0.26	0.27	0.26
Canberra	0.27	0.25 (50%)	0.25	0.25	0.25
Darwin	0.22	0.20 (50%)	0.19	0.20	0.19
Hobart	0.27	0.25 (60%)	0.26	0.25	0.25
Melbourne	0.23	0.22 (55%)	0.22	0.22	0.22
Perth	0.22	0.21 (50%)	0.21	0.21	0.21
Sydney	0.33	0.29 (40%)	0.29	0.29	0.29
Mean	*0.26*	*0.24*	*0.24*	*0.24*	*0.24*

[a] Portion of total tank storage allocated to the environmental flow chamber for the leaking tank, which is fixed over time but varies by location and with system design parameters.

Consistent increases in the environmental benefit of leaking and adaptive rainwater tanks over conventional tanks are demonstrated in all locations (Table 8-4). High compliance (mean of all cities is 0.90) indicates rainwater tanks are capable of restoring aspects of pre-urban stream hydrology without additional WSUD treatment elements, when the connected roof area is considered in isolation. Additional allotment-scale WSUD treatment may be necessary where the connected roof area is a small fraction of the total imperviousness of the allotment, which could potentially be the case. Thus, the second research question is answered: *are other allotment-scale WSUD components needed in conjunction with rainwater tanks to achieve restoration of stream hydrology?*

Table 8-4 Annual average environmental benefit index for base scenario

	***EBI* for tank types**				
	Conventional	**Leaking**	**Adaptive**		
Cities			**Statistics**	**Forecasts**	**Combined**
Adelaide	0.63	0.98 (45%))[a]	0.97	0.98	0.96
Brisbane	0.57	0.86 (40%)	0.89	0.88	0.89
Canberra	0.66	0.97 (50%)	0.98	0.98	0.97
Darwin	0.31	0.74 (50%)	0.74	0.74	0.75
Hobart	0.68	0.99 (60%)	0.99	1.00	1.00
Melbourne	0.69	0.99 (55%)	0.97	1.00	1.00
Perth	0.47	0.81 (50%)	0.81	0.84	0.85
Sydney	0.52	0.84 (40%)	0.84	0.83	0.85
Mean	*0.57*	*0.90*	*0.90*	*0.91*	*0.91*

[a] Portion of total tank storage allocated to the environmental flow chamber for the leaking tank, which is fixed over time but varies by location and with system design parameters.

The water balance results for the base scenario (Fig. 8-2) shows that overflow is reduced by leaking and adaptive rainwater tanks in all cities. For clarity only the adaptive system which incorporates the combined control signal is shown, and is labelled 'A-Comb'.

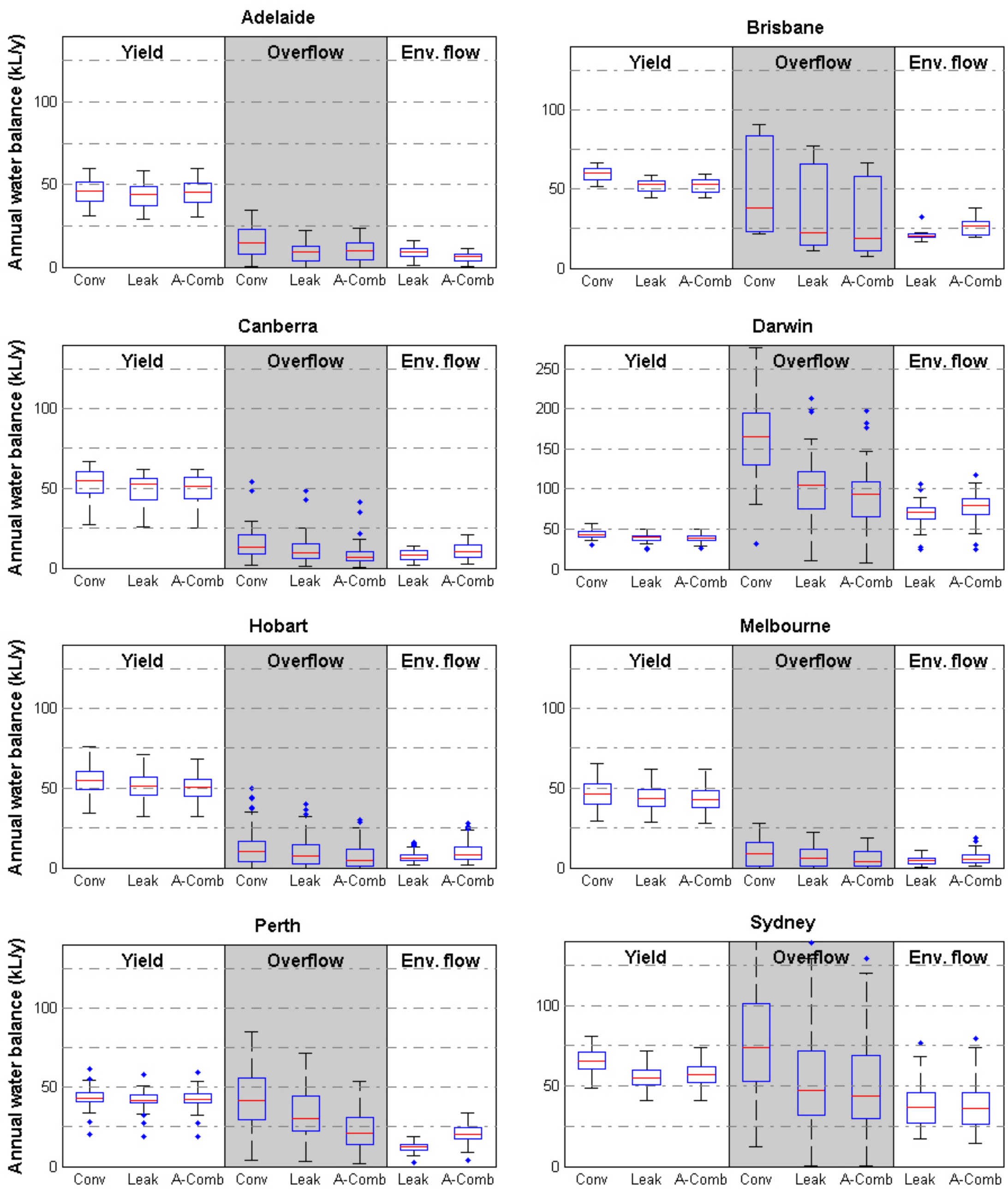


Fig. 8-2 Water balance of base case scenario showing consistent yield for all tanks and reduced overflow for leaking and adaptive (A-Comb) tanks. Note that the y-axis scale is doubled for Darwin.

The hypothetical natural water balance derived for grassed catchments is presented to offer a helpful comparison (Fig. 8-3). The water balance is limited to two components of runoff and evapotranspiration. These quantities are similar to their respective counterparts in the water balance of rainwater tanks. That is runoff is mostly similar to overflow and evapotranspiration is consistent with rainwater yield.

Obvious exceptions are lower yield in Darwin and Perth, due to the seasonality of rainfall.

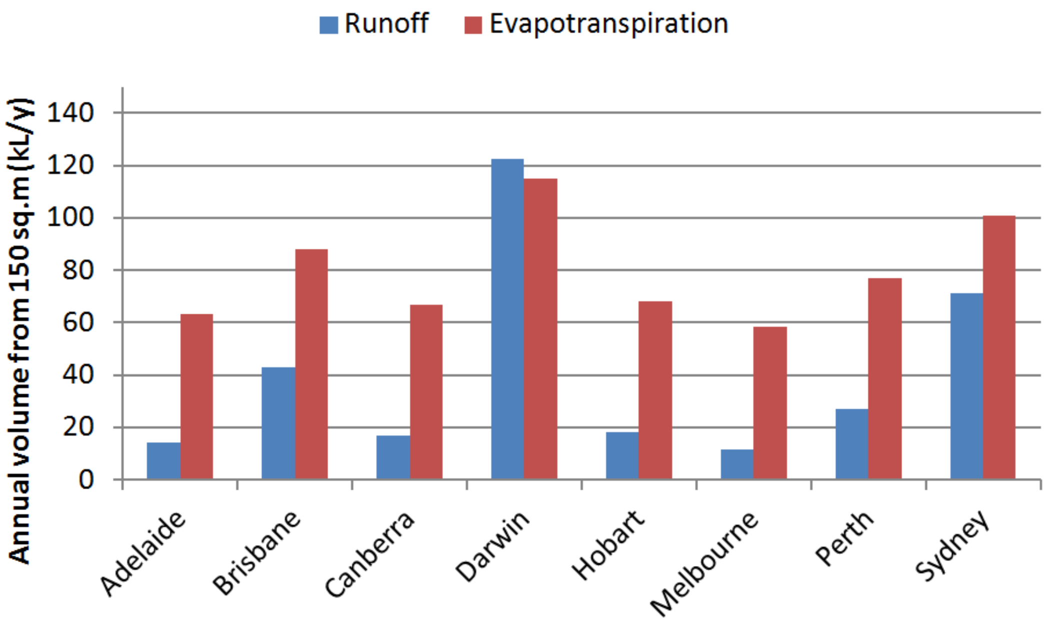


Fig. 8-3 Hypothetical natural water balance for Australian capital cities

Unfortunately, efforts to reduce overflow and create environmental flow have not been without sacrificing yield in Brisbane and Sydney. Otherwise, there is little reduction in rainwater yield across all tanks. Generally the adaptive approach produces greater environmental flow with less yield sacrifice which indicates a marginal improvement over the leaking tank. However these improvements are insufficient to justify broad implementation of this complex approach, at an allotment scale.

The temporal variability of annual yield and environmental flow is reasonably similar among sites, which demonstrates consistent performance can be achieved. A large distribution in annual overflow occurs in sites that have seasonally dominant rainfall (Brisbane, Darwin and Perth) and large variations in annual rainfall (Sydney). This result is typical of fluctuations to pre-urban stream hydrology for these regions.

Annual time-series plots of EBI, VU and SI (Fig. 8-4) shows minimal temporal variation in VU. The variability of EBI is greater and can be negatively correlated with annual rainfall in summer dominant regions (Brisbane and Darwin), positively correlated in winter dominant regions (Perth); and negative correlation in regions where annual rainfall oscillates between wet and dry periods (Sydney). Consistent dual-duty performance is achieved and this relates to extreme rainfall conditions favouring either one of the dual-duties objectives.

An investigation of the EBI sub-indices reveals for most cities flow-frequency compliance is consistently achieved (Fig.8-5). Perth is the obvious exception where the low demand during winter and high rainfall results in excessive frequency of overflow. The volume of excess runoff removed from the catchment is lower in sites with a dominant rain season or with notable variation in annual rainfall (Sydney).

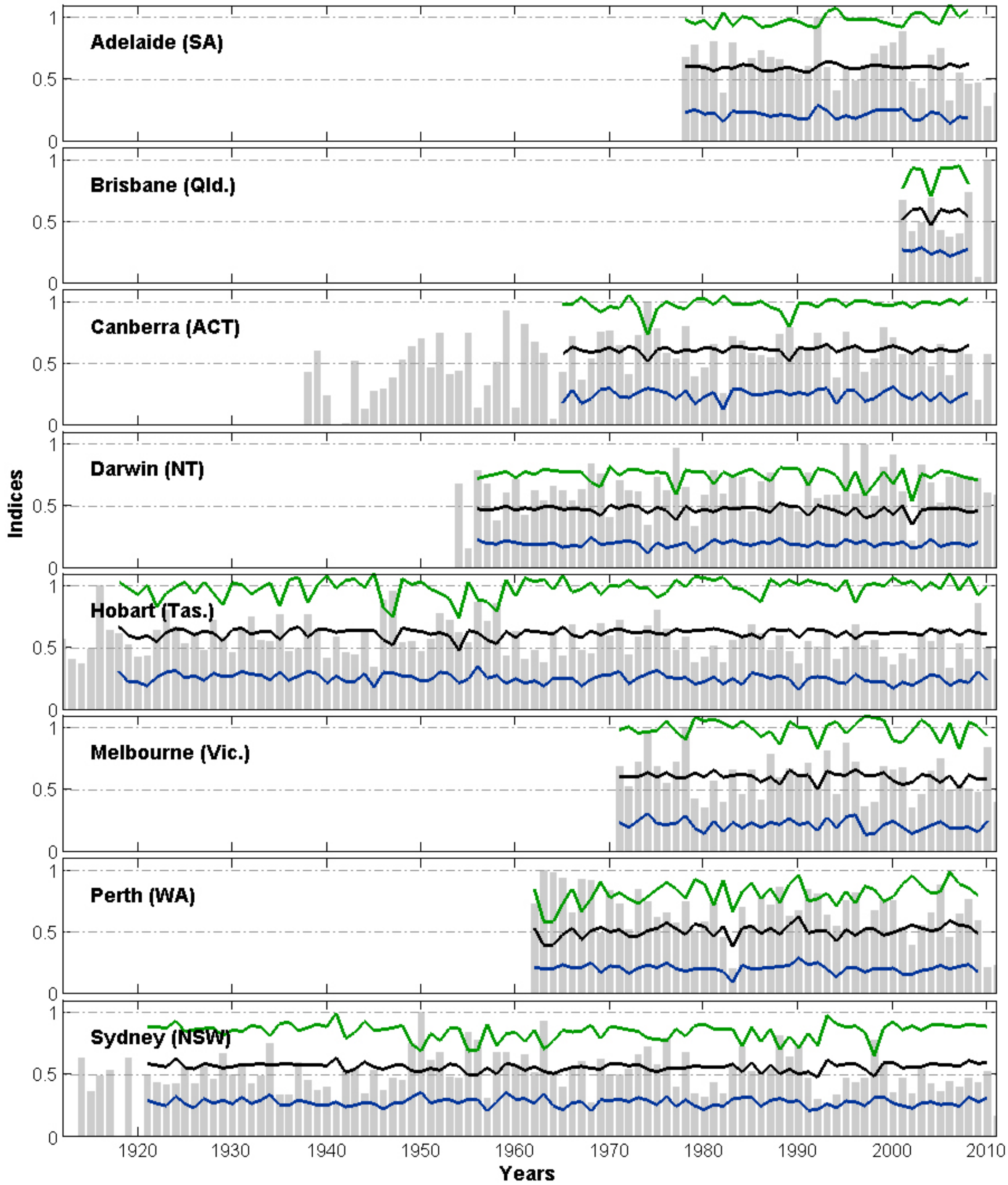


Fig. 8-4 Temporal variation in dual-duty performance of leaking tank for base scenario; annual rainfall standardised by maximum annual rainfall (**grey bars**), environmental benefit index (**green**), volumetric utility (**black**) and supply independence (**blue**).

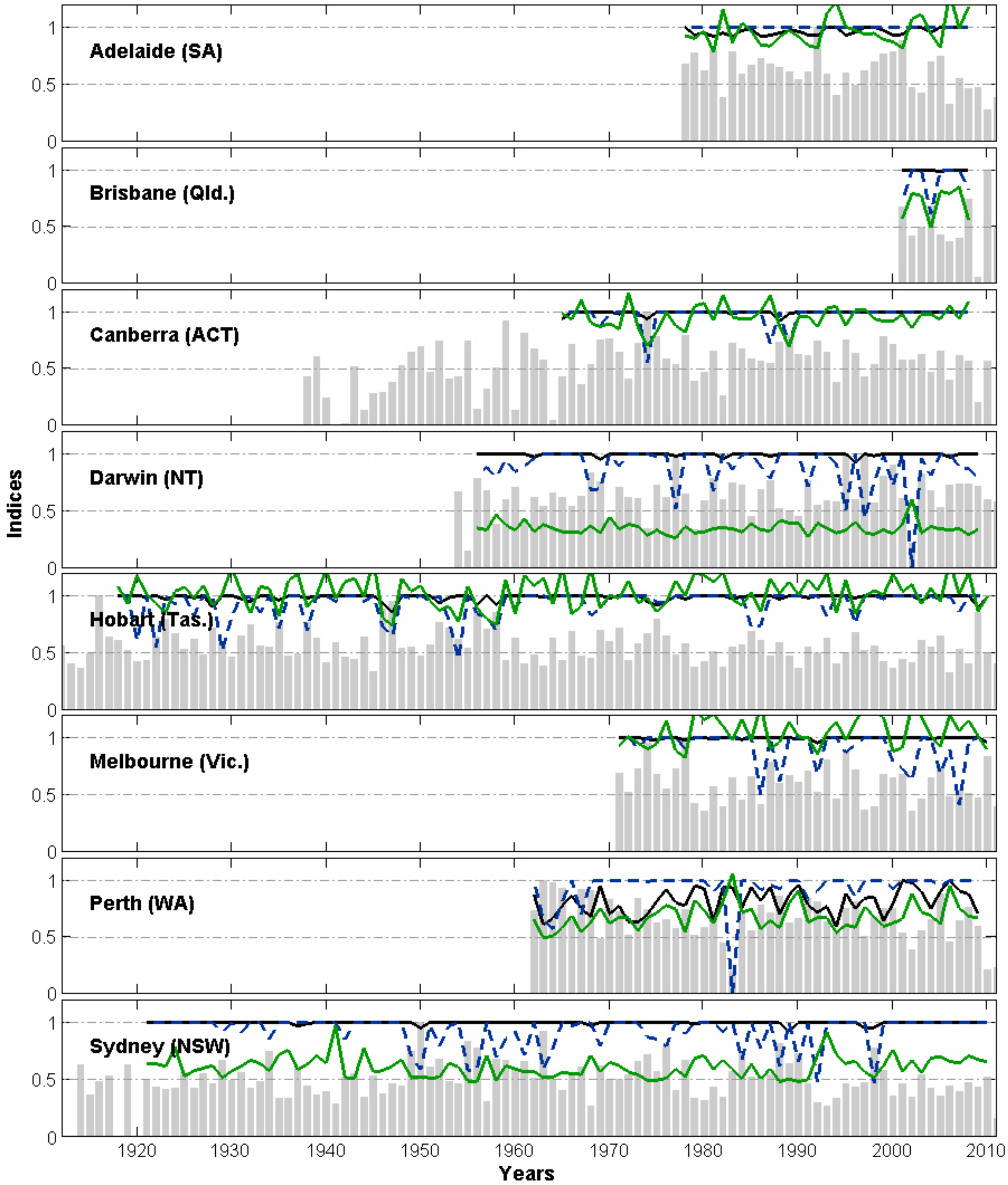


Fig.8-5 Temporal variation of environmental benefit sub-indices for leaking system under base case scenario; rainfall standardised by maximum annual records (**grey bars**), flow-frequency sub-index (**black**), filtered flow volume sub-index (**dashed blue**) and volume reduction sub-index (**green**). Note the occurrence of zero scores for the filtered flow volume.

Zero values for the filtered flow volume occur infrequently when the volume of environmental flow is excessive. That is, when environmental flow generated by the rainwater tank is greater than the combined estimates from the hypothetical pre-urban catchment in forested and pastured conditions.

Additional statistics are shown (Fig. 8-6) including *average annual import water*, all non-rainwater supplied to the household (kL); *annual average household harvest* (kL), the annual rainwater yield plus environmental flow; *environmental flow drought* (days/year), the maximum duration without flow each year; *environmental flow longevity* (days/year), the maximum duration of continuous flow each year; and similarly, *supply drought* (days/year) and *supply longevity* (days/year).

Annual average imported water is similar for hypothetical households in all cities and for all rainwater tank alternatives, being approximately 150 kL or 75% of total demand. This is consistent with field monitoring of rainwater installations in Sydney were most households saved at least 20% of annual municipal water demands (Ferguson 2012). Also, the boxplots show the annual variation is rather small over the simulation period, which in some locations exceeds 90 years. Therefore, for the base scenario, and considering spatial and temporal aspects, rainwater tanks can consistently mitigate residential municipal water demand by 25%, irrespective of their type.

For some locations (Brisbane, Darwin, Perth and Sydney) the annual harvest is notably higher for leaking and adaptive tanks. When considering the minimal change in annual imported water, the leaking and adaptive approaches show their superiority. In all other sites, the annual harvest is higher for leaking and adaptive systems but may be only marginally.

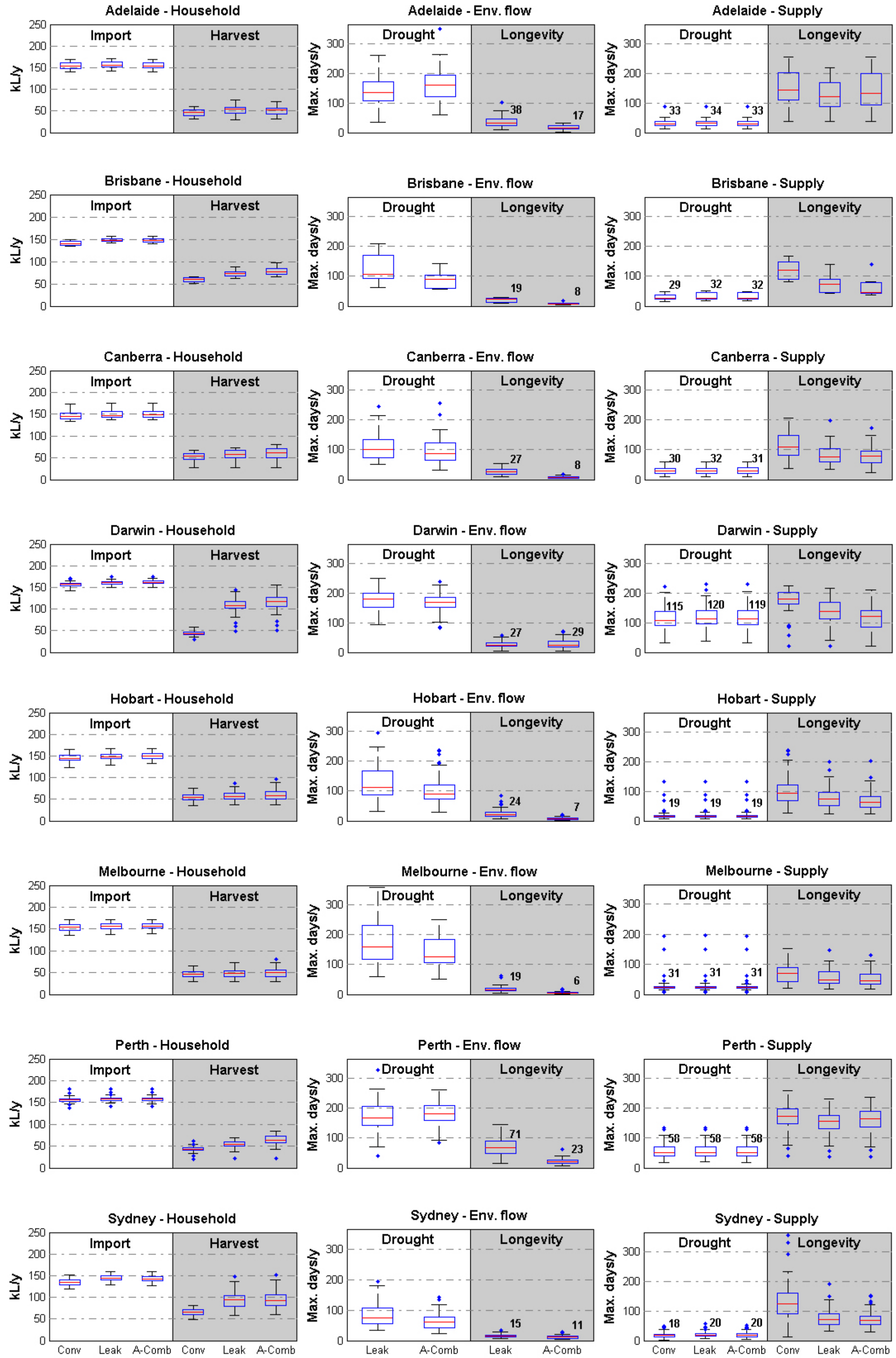


Fig. 8-6 Additional statistics for base case scenario with conventional, leaking and adaptive tanks (combined control signal).

The maximum annual environmental flow drought varies notably in both temporal and spatial aspects. Generally, the longest duration without flow is between 100 and 200 days for the leaking tank and in some locations could be reduced by approximately one month using the adaptive approach. Also, the duration appears to be unrelated to annual rainfall or rainfall seasonality as best results occur in Brisbane and Sydney.

The environmental flow drought seems excessive and therefore, with this metric a slight advantage exists for the adaptive approach as limiting this duration is more consistent with natural conditions. The conventional tank is not shown as environmental flows are not produced.

The maximum annual environmental flow longevity can be significantly longer with leaking tanks, as was anticipated by lower flow rates. Also, elevated environmental flow rates in Brisbane, Darwin and Sydney have not excessively reduced this duration. Thus the environmental flows from leaking tanks are less intermittent and more consistent with the sustained periods of flow or no flow that is characteristic of Australian streams.

The maximum annual supply drought is consistent among all tanks but is longer in locations with a dominant rain season. This demonstrates the leaking and adaptive tanks will not prolong the greatest period that rainwater supplies will be unavailable. A likely cause is that non-seasonal rain events are mostly insufficient to fill tanks and create environmental flow. This phenomenon mimics the pre-urban hydrology, when non-seasonal rainfall is often insufficient of overcome the surface abstractions of saturating vegetation and evapotranspiration. Consequently, the soil moisture content is meagrely increased and the mechanisms for creating stream baseflow are insufficient.

The maximum annual supply period varies notably in spatial and temporal aspects. Very short duration are shown in some locations and this relates to years where missing rainfall observations were included in the analysis and limitations with the numerical approach for defining valid ranges in the data distribution. The leaking and adaptive tanks consistently reduce the longevity or rainwater supply for the maximum annual period by approximately 10 % to 50 %. Fortunately, this has a minimal impact on rainwater yield for most sites, as previously discussed.

Overall from the results of the base scenario, the adaptive approach offers limited superiority over the leaking rainwater tank and the added complexity is not justified. Thus, further investigation of dual-duty performance is refined to comparisons of conventional and leaking tanks.

8.4 Extended dual-duty performance assessment

The dual-duty performance assessment is extended to answer the remaining research question: to what extent does the dual-duty performance vary over the spectrum of urban residential living in Australia? Furthermore, in Chapter 6, it became apparent that optimum values could exist for rainwater demand; environmental flow rate and volume; and total tank volume. Finding these optimum values will promote the broader relevance of dual-duty rainwater tanks.

Following on from the results of the dual-duty sensitivity analysis in Chapter 6, parameters will be investigated in order of sensitivity to VU estimates. Besides rainfall distribution, the volume of the environmental flow chamber, expressed as a percentage of total tank volume, and connected roof area were the most significant parameters. Thus, an analysis of the optimum chamber volume was conducted for the typical range of connected roof areas with all other parameters in accordance with the base scenario (Table 8-5). Although not shown, a similar response to the VU was discovered with altering the connected roof area for conventional rainwater tanks.

The environmental flow chamber volume, which was optimised for dual-duty performance, was positively correlated to the connected roof area in sites with a dominant rain season (Darwin and Perth). Otherwise, there was either no change in chamber volume or a negative correlation. The negative correlation is explained by the filtered-flow volume sub-index in the EBI. With an increased roof area, stored water more frequently fills the environmental flow chamber. Thus, in some locations, the chamber volume must be reduced to prevent excessive environmental flows. It may be necessary to conduct further research to completely comprehend the relationship between roof area and optimum environmental flow chamber volume.

Table 8-5 Leaking tank optimum environmental flow chamber volume (%) and dual-duty performance by roof area

	100 m²				200 m²			
Cities	**%**	VU	SI	EBI	**%**	VU	SI	EBI
Adelaide	60	0.60	0.17	1.03	35	0.58	0.25	0.90
Brisbane	40	0.59	0.23	0.94	40	0.54	0.29	0.80
Canberra	60	0.61	0.19	1.02	45	0.59	0.28	0.91
Darwin	35	0.50	0.19	0.80	65	0.44	0.19	0.69
Hobart	75	0.60	0.19	1.02	50	0.62	0.29	0.94
Melbourne	75	0.59	0.16	1.03	45	0.61	0.26	0.96
Perth	45	0.56	0.18	0.93	60	0.47	0.22	0.72
Sydney	40	0.58	0.27	0.90	40	0.54	0.31	0.78

Refer to Tables 8.2, 8.3 and 8.4 for intermediate 150 m² roof area scenario. Note that EBI greater than 1 suggest the rainwater tank is using close to all water which drains to it and effectively compensating for impervious areas other than those connected (Walsh *et al.* 2012).

Also discovered in the dual-duty sensitivity analysis in Chapter 6 was the negative correlation that tank volume and rainwater demand has to the EBI, while these parameters have a positive correlation to VU and SI. An analysis was conducted to determine the optimum environmental flow chamber volume for typical ranges in these parameters (Table 8-6 and Table 8-7). It was discovered that the environmental flow chamber volume is positively correlated to total tank volume and rainwater demand in all cities.

Table 8-6 Leaking tank optimum environmental flow chamber volume (%) and dual-duty performance by tank volume

	2.5 kL				7.5 kL			
Cities	**%**	VU	SI	EBI	**%**	VU	SI	EBI
Adelaide	35	0.55	0.19	0.91	50	0.62	0.23	1.00
Brisbane	45	0.49	0.20	0.78	40	0.60	0.30	0.90
Canberra	45	0.54	0.20	0.89	50	0.63	0.27	1.00
Darwin	70	0.42	0.15	0.69	40	0.49	0.22	0.76
Hobart	55	0.57	0.21	0.93	65	0.64	0.27	1.00
Melbourne	45	0.56	0.19	0.94	65	0.62	0.23	1.00
Perth	70	0.46	0.17	0.75	30	0.60	0.34	0.86
Sydney	45	0.50	0.22	0.77	35	0.60	0.33	0.87

Refer to Tables 8.2, 8.3 and 8.4 for intermediate 5 kL tank volume scenario.

By increasing the environmental flow chamber volume the EBI became positively correlated to tank volume and rainwater demand. This is a desirable result which encourages increasing the components of rainwater systems.

Table 8-7 Leaking tank optimum environmental flow chamber volume (%) and dual-duty performance by rainwater demand

	44 kL/y				176 kL/y			
Cities	**%**	VU	SI	EBI	**%**	VU	SI	EBI
Adelaide	15	0.51	0.16	0.86	70	0.65	0.26	1.03
Brisbane	35	0.50	0.19	0.80	45	0.61	0.33	0.88
Canberra	25	0.53	0.18	0.87	75	0.64	0.28	1.00
Darwin	50	0.41	0.12	0.71	50	0.55	0.32	0.77
Hobart	30	0.42	0.14	0.70	80	0.64	0.28	1.00
Melbourne	25	0.56	0.18	0.94	80	0.62	0.23	1.02
Perth	30	0.42	0.14	0.70	80	0.61	0.29	0.92
Sydney	40	0.49	0.20	0.79	45	0.61	0.37	0.86

Refer to Tables 8.2, 8.3 and 8.4 for intermediate 87 kL/y rainwater demand scenario.

An analysis of the scale of the overall rainwater systems was conducted based on the parameters previously defined (Table 3-3) and water use scenarios (Table 4-2). Two scenarios were established to represent high and low urban densities. The high density scenario comprises a hypothetical small unit (100 m^2 connected roof area), occupied by three people or less and where no outdoor water use is from the small 2.5 kL rainwater tank (rainwater demand 44 kL). The low density scenario comprises a hypothetical larger house (200 m^2 connected roof area), occupied by three or more people and where outdoor water use is from the large 7.5 kL rainwater tank (rainwater demand 176 kL). In all sites, environmental flow chamber volume and the dual-duty performance is positively correlated to the scale of the rainwater system, or negatively correlated to urban density (Table 8-8). This does not suggest a hydrologic economy of scale exists but rather the larger rainwater demand and tank volume that is typical in low urban development is beneficial for dual-duty rainwater tanks.

Table 8-8 Leaking tank optimum environmental flow chamber volume (%) and dual-duty performance by urban density

	High urban density				Low urban density			
Cities	**%**	***VU***	***SI***	***EBI***	**%**	***VU***	***SI***	***EBI***
Adelaide	25	0.58	0.21	0.95	70	0.63	0.23	1.02
Brisbane	45	0.53	0.23	0.84	45	0.59	0.29	0.88
Canberra	30	0.58	0.23	0.94	75	0.62	0.25	1.00
Darwin	50	0.46	0.18	0.74	50	0.50	0.25	0.75
Hobart	40	0.60	0.24	0.97	80	0.62	0.25	1.00
Melbourne	40	0.59	0.20	0.97	80	0.61	0.21	1.02
Perth	40	0.50	0.20	0.80	80	0.56	0.24	0.88
Sydney	35	0.54	0.26	0.82	55	0.59	0.31	0.86

Note that high urban density comprises roof area: 100 m^2; total tank volume: 2.5 kL; and rainwater demand: 44 kL without outdoor use. Low urban density is roof area: 200 m^2; total tank volume: 7.5 kL; and rainwater demand: 176 kL including 17% outdoor use. Refer to Tables 8.2, 8.3 and 8.4 for medium urban density scenario.

8.5 Summary of rainwater tank performance assessment

Active management of environmental flows from rainwater tanks was examined and based on modifying the storage of the virtual environmental flow chamber in accordance with the severity of rainfall statistics, rainfall forecasts, or a combination of both controls.

The mean monthly frequency of days with rainfall above minor abstractions was adopted due to frequency of rainfall being linked to the occurrence and duration of stream baseflow, as discussed in Section 3.5. Where this frequency was 15 days or higher, the volume of the environmental flow chamber was set to 90% of the total tank volume for that month. The best results for this method were anticipated in locations where the seasonality of rainfall frequency is highly evident (Adelaide, Darwin and Perth). However, further analysis showed superior results did not occur in these locations.

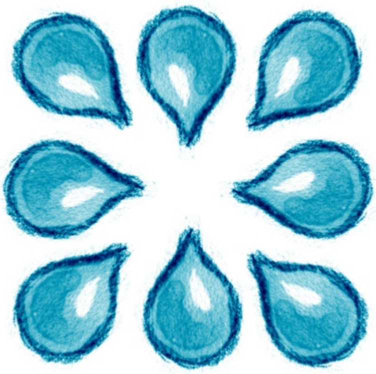
On a daily basis, the six day mean rainfall forecast from a 2 day horizon was adopted as a control signal. Where the mean was 3.5 mm/d or higher the volume of the environmental flow chamber was increased to 90% of the total tank volume for that day. By establishing a control signal from rainfall forecasts, environmental flow could potentially occur prior to rainfall and prior to tank overflow. It was anticipated that this approach would be superior at maintaining rainwater yield, irrespective of the location or rainfall seasonality. However, further analysis showed this approach was similar to monthly rainfall statistics and the leaking rainwater tank.

A combined control signal was examined base on rainfall statistics and forecasts. It was anticipated that this approach would extend the duration of environmental flow by potentially enabling flow before, during and after a rain event. However, this was not the case and the leaking rainwater tank was consistently superior at achieving sustained periods of environmental flow.

The performance of conventional, leaking and adaptive rainwater tanks was examined in all capital cities and with a base scenario that represents the central range of design parameters typically found in urban settings. In nearly all cases the leaking tank was superior, especially considering the simplicity of this approach. An extended analysis was then performed on the leaking tank to establish the potential performance over the spectrum of urban living. These results are applied in Chapter 9 to establish a rapid method to determine the performance of leaking rainwater tanks.

Chapter 9 Rapid Performance Estimation

Dimensionless relationships are established from storage and discharge fractions to statistically determine the volumetric utility, supply independence and the environmental benefit index. Relationships are based on the results of simulations scenarios in Chapter 8. These relationships facilitate rapid performance estimation of leaking and conventional rainwater tanks by applying rainfall statistics and design parameters including roof area, tank volume and rainwater demand.



9.1 Introduction

It is well-known that Australian rainfall varies significantly in temporal and spatial aspects. The national average rainfall (Fig. 9-1) and rainfall classification zones (Fig. 5-1) demonstrate the spatial extremes, while the temporal variation is evident at annual (Fig. 4-4) and monthly (Fig. 7-3) time-scales. Sensitivity analyses (Fig. 3-4 and Fig. 6-4) have demonstrated that estimates of rainwater yield, and dual-duty performance are particularly sensitive to rainfall distribution. It was therefore suggested in Chapter 3 that a method for linking rainfall statistics to rainwater tank performance be established to increase the relevance of research results. Otherwise, results may be relevant only to the study site and time, in addition to other constraints of simulated design parameters and water use habits.

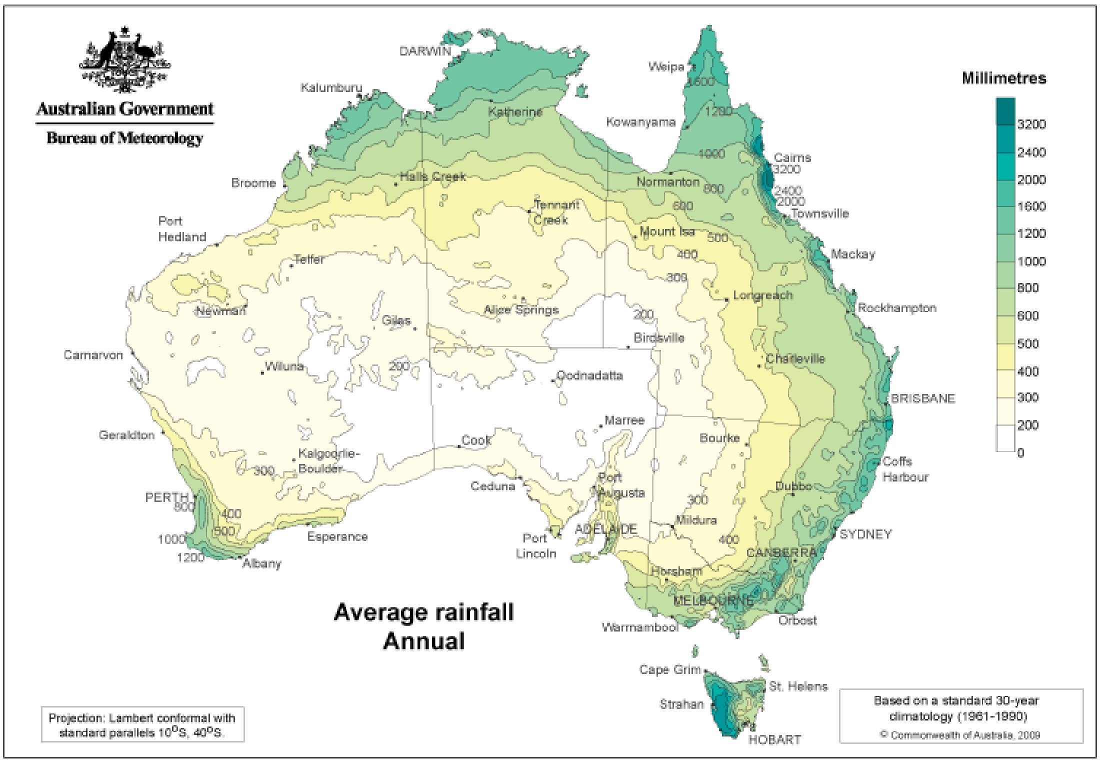


Fig. 9-1 Annual rainfall variability in Australia. Source: (BoM 2012b)

Typical urban residential rainwater tanks have a within-year critical period of approximately three to four weeks. This is the time for the tank to empty from full under normal water use and without inflow (McMahon & Mein 1978). Given this period is brief, the frequency of rainfall is critical to the reliability of rainwater tanks. Thus, annual rainfall is not always a good indicator of potential system reliability or rainwater yield.

Many have attempted to generalise rainwater harvesting performance to facilitate broad-scale application and design of rainwater tanks. Jenkins (2007) developed a statistical relationship between water saving efficiency (the ratio of rainwater yield to rainwater demand) and rainfall seasonality. However, application of this relationship was less reliable than first reported, with $R^2 < 0.3$ for the base scenario.

Hanson *et al.* (2009) attempts to derive tank volume from daily rainfall statistics to meet levels of supply reliability. However, rainwater harvesting performance is not particularly sensitive to tank volume (Fig. 3-4 and Fig. 6-4) which limits the value of these relationships.

Khastagir (2008) defines dimensionless relationships and quantifies the reliability of rainwater systems throughout the Melbourne district. Unfortunately, a single general relationship that incorporates the principal design parameters of rainwater tanks is not reported. Like Khastagir, many others fall short of incorporating the design parameters of location, roof area, rainwater demand and tank volume into a single general relationship. Studies by region include Australia (Barry & Coombes 2008; Mitchell *et al.* 2008b; Beal *et al.* 2010; Imteaz *et al.* 2011; Neumann *et al.* 2011; Rahman *et al.* 2012), Brazil (Ghisi 2010), Germany (Herrmann & Schmida 1999), Italy (Palla *et al.* 2011; Campisano & Modica 2012), South Korea (Mun & Han 2012), Taiwan (Liaw & Tsai 2004), the United Kingdom (Fewkes 2000a; Palla *et al.* 2012) and the United States (Hanson *et al.* 2009).

The aim of this chapter is to establish a general relationship to derive the volumetric utility VU, supply independence SI and the environmental benefit index EBI over the scenarios previously studied for leaking and conventional rainwater tanks. These relationships will establish a rapid method for design, and performance estimation of dual-duty rainwater tanks which is necessary to enhance standard practice and expedite the development of water sensitive cities.

9.2 Methodology

Many of the aforementioned studies apply dimensionless indices based on the storage fraction consistent with that reported by Fewkes (2000a). Similarly, the storage fraction will form the basis of the dimensionless analysis to follow but the limited correlation between annual rainfall and rainwater performance will be remedied by introducing new rainfall statistics.

This chapter concludes with a application of the principles discussed by providing a flowchart designed to assist the practitioner to estimate the dual-duty performance of leaking rainwater tanks.

9.2.1 Statistical representation of rainwater tank failure

In terms of the water supply duty, it is fundamental to accurately estimate rainwater yield. Therefore, statistical representations of the mode of failure are based on identifying missed opportunities to increase rainwater yield.

Under normal operation there are three modes of failure or missed opportunities for a rainwater tank: (1) *empty* and unable to meet demand, from an extended period of low or no rainfall; (2) *sudden overflow* and unable to increase yield, from a single large rain event; and (3) *continuous overflow* from continuous or near continuous rainfall over a rain dominant period. Representations of these failure modes are derived from statistical analysis of daily rainfall observations.

By basing the relationship on daily rainfall observations the extended periods with limited rainfall are included in the analysis and the first failure mode is addressed. The bias that excessive daily rainfall introduces to the relationship between rainwater yield and annual rainfall can be removed by capping observations at a maximum daily threshold.

The average daily capped rainfall P_{cap} (mm/d) can be determined with (9-1), where P_d is the rainfall on day d, P_{max} is the maximum daily threshold and D_{total} is the total number of observations in the time-series.

$$P_{cap} = \sum_{i=1}^{Dtotal} \min(P_d, P_{max}) \Big/ D_{total} \qquad \textbf{(9-1)}$$

Through a process of iteratively adjusting the maximum daily threshold a value of 17 mm was desirable for all locations. A higher threshold introduces bias from large rain events that would typically overwhelm the tank, whereas a lower threshold removes rain events that are significant for filling the tank. The adopted threshold corresponds to half filling a 5 kL tank with a 150 m^2 roof area which is consistent with the central range of parameters values adopted in the dissertation.

The frequency of rain days indicates how broadly the rainfall is distributed throughout the year. The ratio of precipitation days R_{pd} (unitless) can be determined with (9-2), where D_p is the number of days where rainfall is above the accumulative daily initial loss and first flush abstractions of 0.8 mm, as defined in Section 2.7.

$$R_{pd} = {D_p}/{D_{total}} \tag{9-2}$$

R_{pd} values approaching zero indicate that rainfall occurs rarely and this would create a challenging environment for rainwater harvesting. Moderate values indicate that rainfall is fairly infrequent and excessive daily rainfall is possible. Values approaching one suggest that rainfall is potentially evenly distributed throughout the year, which is the most desirable condition for rainwater harvesting. Thus, rainwater yield could be positively correlated to this ratio.

Continuous or near continuous rainfall can be identified by the seasonality of rainfall. The ratio of precipitation seasonality R_{ps} (unitless) can be determined with (9-3), where P_{total} is the total accumulated rainfall (mm), P_{win} is the total winter rainfall from May to October (mm) and P_{sum} is the total summer rainfall from November to April (mm). These periods are consistent with methods to map rainfall seasonality throughout Australia (BoM 2011).

$$R_{ps} = {\max(P_{win}, P_{sum})}/{P_{total}} \tag{9-3}$$

R_{ps} values approaching 0.5 indicate that rainfall is uniformly distributed between winter and summer periods, which is desirable. Values approaching one indicate that rainfall is highly seasonal and continuous or near continuous rainfall is highly likely. Thus, rainwater yield could be negatively correlated to this ratio.

Finally, rainwater yield can be estimated from the precipitation yield index PYI (mm/d). PYI is derived by combining the average daily capped precipitation with the ratios of precipitation days and seasonality. To increase the regression of PYI to rainwater yield, coefficients were trialled for the precipitation ratios. The ratio of precipitation days was consistently less significant than precipitation seasonality. Consequently, the increased rainwater yield attributed to high R_{pd} is less than anticipated and a reduction factor of 2 was necessary. PYI can be determined with (9-4) and is expected to positively correlate with rainwater yield.

$$PYI = \max\left(0, P_{cap}\left(1 + \frac{R_{pd}}{2} - R_{ps}\right)\right) \qquad \textbf{(9-4)}$$

However, PYI only considers rainfall and there are other design parameters which rainwater performance is particularly sensitive to, such as, connected roof area, tank volume and rainwater demand.

9.2.2 Dimensionless storage fraction

The metrics of supply independence, environmental benefit and volumetric utility are dimensionless so it follows that regression to dimensionless indices could establish a rapid method to estimate rainwater tank performance.

The storage fraction, which is the ratio of system volume to inflow volume, is often used in dimensionless analysis of rainwater yield. The fraction was introduced by Fewkes (2000a), as described in Section 4.3.1. The storage fraction includes rainwater tank design parameters of the volume of the water supply chamber V_{ws} (m^3) and system inflow as the product of the connected roof area A (m^2), the precipitation yield index PYI (mm/d) and a duration factor to satisfy dimensions. Additionally, rainwater demand should be included, at this is a significant design parameter. It is anticipated that the rainwater demand standardised by the central value of total household demand (200 kL/y) would be related to supply independence.

Another characteristic of rainwater yield curves is they approach a horizontal asymptote as the tank volume increases. Thus, a storage limitation needs to be included in the fraction. Finally, to plot a horizontal asymptote that is approached from zero, it is necessary to take the inverse of the traditional storage fraction. The storage fraction SF (unitless) will be applied to rapidly determine the supply independence of conventional and leaking rainwater tanks for the scenarios discussed in Chapter 8 and can be determined with (9-5), where a is duration factor (days), b is the volume limitation factor (m^3) and c is a regression calibration factor.

$$SF = {}^{(A \times PYI \times a)}\!\Big/_{(b - V_{ws})} \times \left({}^{D_r}\!/_{200} \right)^{c} \tag{9-5}$$

9.2.3 Dimensionless discharge fraction

Assessment of the environmental benefits of rainwater tanks is based on discharge compliance by mitigating excess runoff and returning diminished environmental flows. Thus, it would be reasonable to base a dimensionless performance index for the environmental benefit index on a discharge fraction. This suggests the storage volume is not a critical parameter, which is consistent with the results of the dual-duty sensitivity analysis in Section 6.4. However, storage is an essential design parameter and will be included as a separate factor that is standardised by the central value of the range studied.

The dual-duty sensitivity analysis also demonstrates that rainwater yield is a significant factor. For consistency, the dimensionless fraction of rainwater demand to total household demand will be included.

The ratio of environmental flow rate to runoff rate determined as the product of A and PYI could provide a basis to rapidly determine the environmental benefit index. The discharge fraction DF (unitless) can be determined with (9-6), where EF is the daily environmental flow rate (L/day), and c and d are regression calibration factor.

$$DF = {}^{EF}\!/_{(A \times PYI)} \times \left({}^{D_r}\!/_{D_t}\right)^c \times \left({}^{V_t}\!/_5\right)^d \tag{9-6}$$

9.2.4 Environmental flow rates

The optimum environmental flow rate for the leaking rainwater tank was determined for all capital cities and a range of 100 to 900 L/day was reported (Table 8-2). As previously mentioned, the practitioner should consider catchment specific conditions which influence the occurrence of baseflow (Hamel *et al.* 2013). The range is significant and failure to adopt a suitable flow rate can have a significant impact on the performance of leaking rainwater tanks, and the environment. Thus, a method to rapidly determine flow rates is necessary but would be limited by the refined research scope.

9.2.5 Environmental flow chamber storage percentage

Similar to the environmental flow rates, a large range of 15 to 80% was found for the optimum percentage of tank storage allocated to the environmental flow chamber. This parameter is also a significant factor for the performance of leaking rainwater tanks and must be included to complete the rapid performance assessment.

9.3 Results and discussion

Results presented follow the phases of the methodology where the precipitation yield index PYI was defined, followed by the storage fraction SF and the discharge fraction DF, which forms the basis of the dimensionless relationships with performance metrics of supply independence SI and environmental benefit index EBI, respectively.

9.3.1 Precipitation yield index

For the leaking tank and the base scenario (connected roof area of 150 m^2, total tank volume of 5 kL and average annual rainwater demand of 87 kL), the precipitation yield index has a good correlation (R^2 = 0.92) to the rainwater yield estimated from UrbanTank for all Australian cities (Fig. 9-2). Thus, the average annual rainwater yield Y can be determined for potentially any location in Australia from (9-7), for a leaking rainwater tank and for the base scenario design parameters.

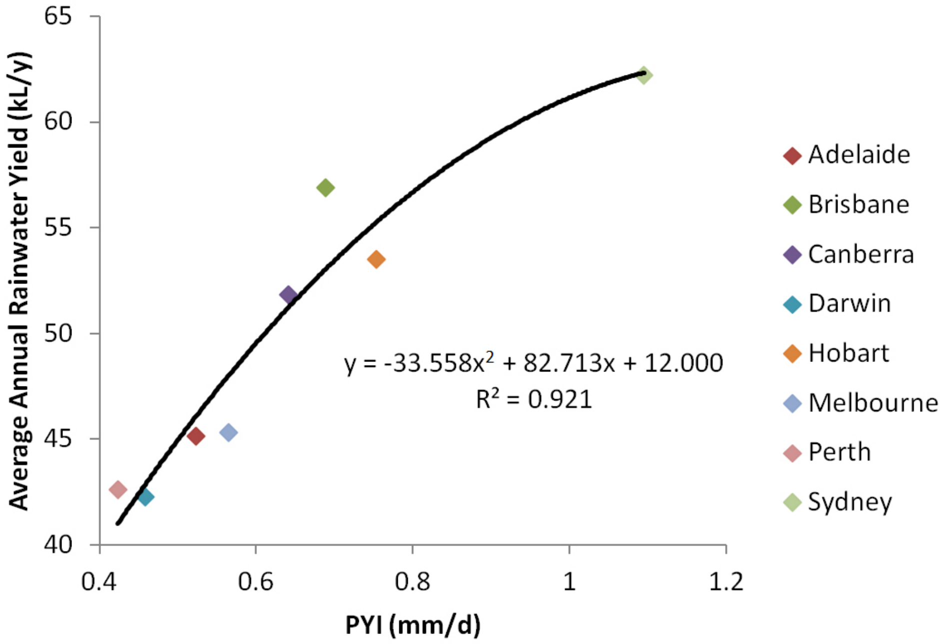


Fig. 9-2 Relationship between rainwater yield and precipitation yield index for leaking tank and the base scenario

$$Y = -33.56 \times PYI^2 + 82.71 \times PYI + 12 \quad \textbf{(9-7)}$$

Average annual PYI values for Australian capital cities typically range from less than 0.5 in locations with dominant rainfall seasonality to more than 1.0 in locations where rainwater harvesting is highly desirable such as Sydney (Table 9-1).

Table 9-1 Precipitation yield indices for Australian capital cities

Site	P_{cap} **(mm/d)**	R_{pd}	R_{ps}	PYI **(mm/d)**
Adelaide	1.31	0.23	0.71	0.52
Brisbane	1.61	0.21	0.68	0.69
Canberra	1.27	0.18	0.59	0.64
Darwin	2.42	0.23	0.93	0.46
Hobart	1.37	0.25	0.58	0.75
Melbourne	1.10	0.20	0.59	0.57
Perth	1.61	0.21	0.84	0.42
Sydney	2.05	0.27	0.61	1.09

The long-term trend in PYI for all capital cities (Fig. 9-3) demonstrates regions with high rainfall seasonality (Darwin and Perth) consistently have poor expectations of rainwater yield (low PYI values). This is despite extreme annual rainfall consistently occurring in Darwin. Sydney and Hobart show the highest potential and in these cities rainfall is reasonably uniform throughout the year. The PYI closely correlates to the standardised rainfall in Sydney but this is an exception. All other sites demonstrate that annual rainfall is not a good indication of potential rainwater yield.

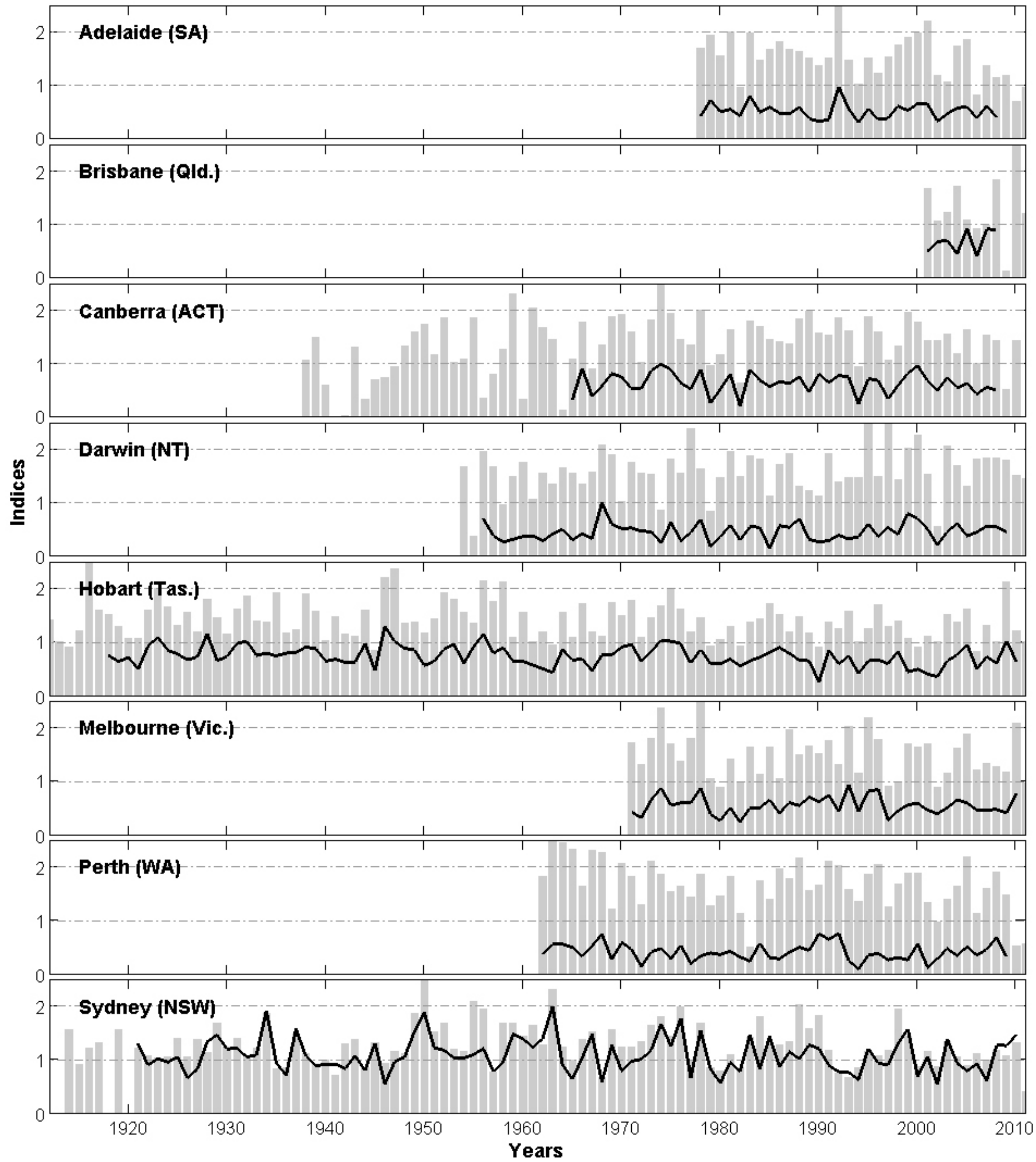


Fig. 9-3 Long-term trend in precipitation yield index for Australian capital cities; annual rainfall standardised by maximum annual rainfall (**grey bars**) and precipitation yield index (**black**)

Like annual rainfall (Fig. 4-4) and annual predicted outdoor water use (Fig. 5-10), PYI can vary significantly over time. There appears to be no long-term annual trend in PYI for all sites studied besides the high to low oscillation which has a 10 to 13 year frequency in Sydney, which was discussed in Section 4.3.3.

Analysis of the components of PYI reveal that capping daily precipitation has little impact in Adelaide and Perth (Fig. 9-4). In these locations the daily rainfall rarely exceeds 30 mm. The ratio of precipitation days is reasonable constant in temporal and spatial aspects. The ratio of precipitation seasonality does not appear to correlate with annual rainfall at any of the sites. Thus, the ratio of precipitation seasonality appears to be the critical component in defining PYI.

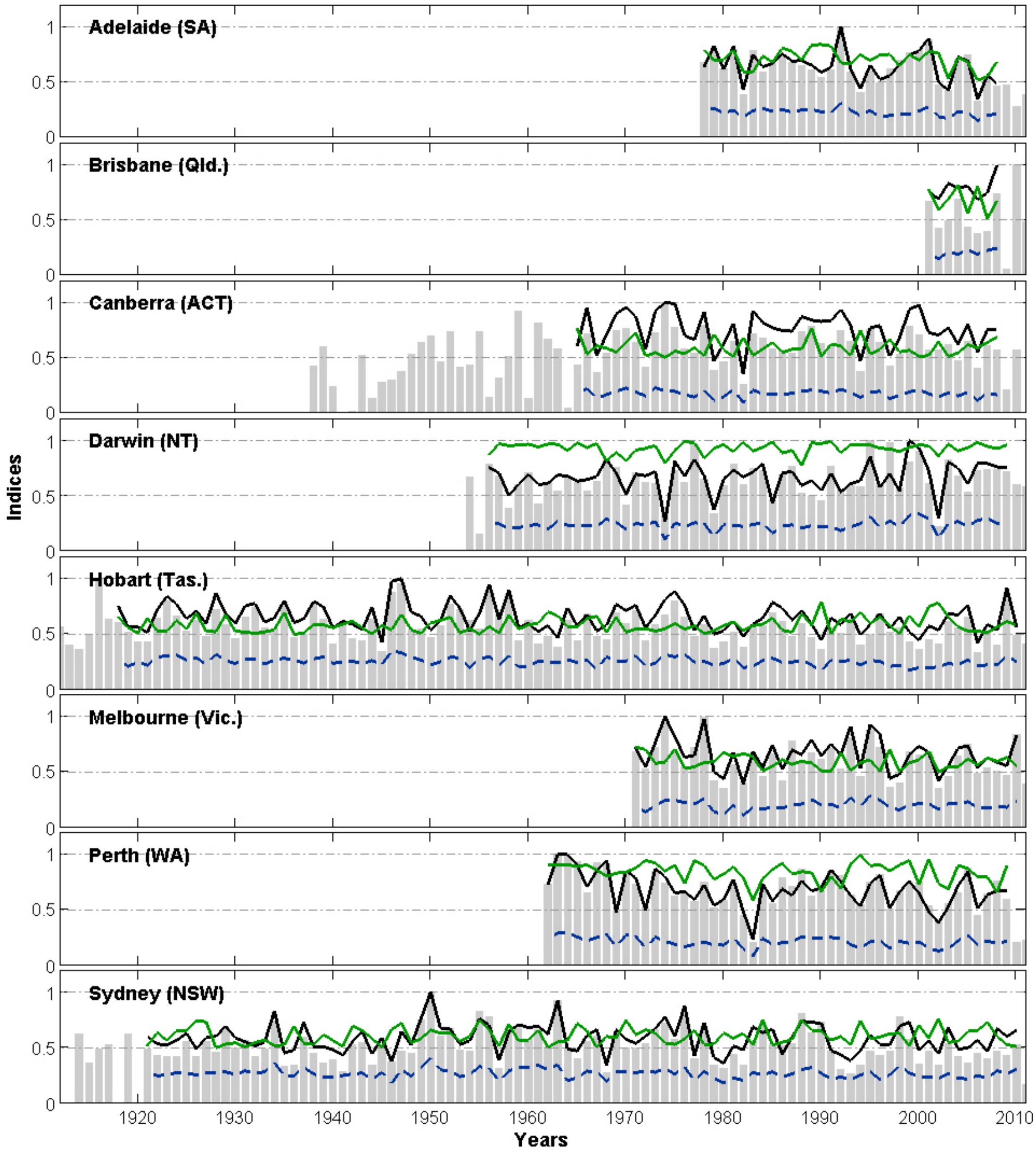


Fig. 9-4 Long-term trend in precipitation yield sub-indices; annual rainfall standardised by maximum annual rainfall (**grey bars**), standardised capped precipitation (**black**), ratio of precipitation days (**broken blue**) and ratio of precipitation seasonality (**green**).

9.3.2 Environmental flow rate

A step-wise linear relationship to the capped daily precipitation was derived for the environmental flow rates EF (L/day), which can be determined with (9-8).

$$EF = \begin{cases} 850 \times P_{cap} - 1023, & P_{cap} \geq 1.3 \\ 100, & \text{otherwise} \end{cases} \tag{9-8}$$

This relationship (Fig. 9-5) is valid for the range in design parameters studied in Chapter 8. One notable outlier exist which represents Perth. Closer inspection found that desirable results were achieved for Perth while flow rates were 300 L/day or less which is consistent with the step-wise linear regression.

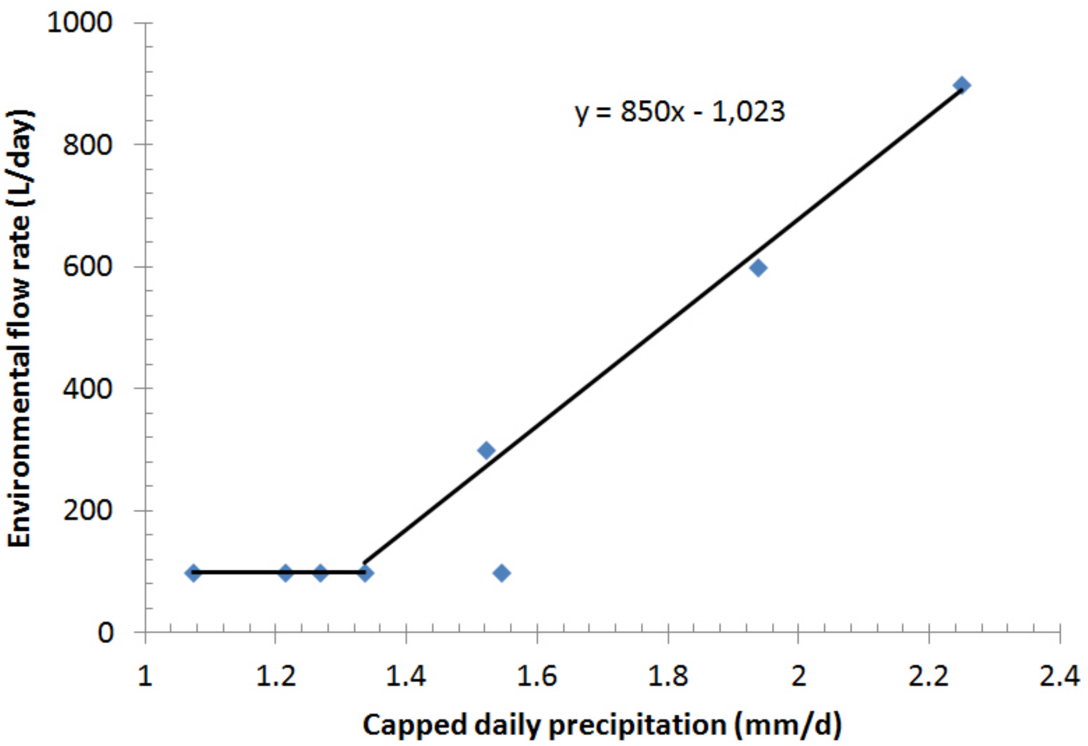


Fig. 9-5 Relationship between capped daily precipitation and environmental flow rate

An alternative approach for calculating desirable environmental flow rates could be based on catchment specific drivers for stream baseflow. The reader is directed to Hamel *et al.* (2012) for related research. Alternatively the product of roof area and soil permeability could provide an avenue for further research.

9.3.3 Environmental chamber storage percentage

The task of obtaining a relationship to the optimised storage of the environmental flow chamber proved to be very challenging. This relationship is based on a range of values that can occur for rainfall, roof area, rainwater demand, tank volume and environmental flow rates and the optimisation occurs for two performance metrics which themselves are dependent on many other peripheral relationships. Thus, general guidance is given for approximating the optimised environmental flow chamber in absence of using the UrbanTank software.

In locations where EF is 300 to 600 L/d a suitable chamber volume would be 40% of the total tank volume. In locations with EF exceeding 600 L/day this percentage could be increased to 50%. In locations where the environmental flow release rate is less than 300 L/d other design parameters are significant (Table 9-2) and interpolation may be necessary depending on the design proposed.

Table 9-2 Guidelines for optimum environmental flow chamber as a percentage of total tank volume P_{EF}

Design parameter	Low range	High range
Rainwater demand D_r	< 50 kL/y	>100 kL/y
	25%	75%
Connected roof area A	≤ 100 m^2	≥ 200 m^2
	65%	50%
Total tank volume V_t	< 3 kL	> 7 kL
Uniform rainfall	45%	50%
Seasonally dominant rainfall[a]	70%	35%

[a] Seasonally dominant rainfall is when $R_{ps} \geq 0.8$

Thus, the volume of the water supply chamber is determined with (9-9), where P_{EF} is determined from Table 9-2.

$$V_{WS} = (1 - P_{EF}) \times V_t \tag{9-9}$$

9.3.4 Dimensionless storage fraction

Regression confidence between the dimensionless storage fraction and supply independence estimates from Chapter 8 was refined by iteratively adjusting the duration factor a (days), the volume limitation factor b (m^3) and the demand ratio regression factor c (unitless). The calibrated storage fraction can be determined with (9-10) and a reasonable regression confidence of $R^2 = 0.86$ was achieved (Fig. 9-6).

$$SF = {(A \times PYI \times D_r)}\Big/{((8 - V_{ws}) \times 8000)} \tag{9-10}$$

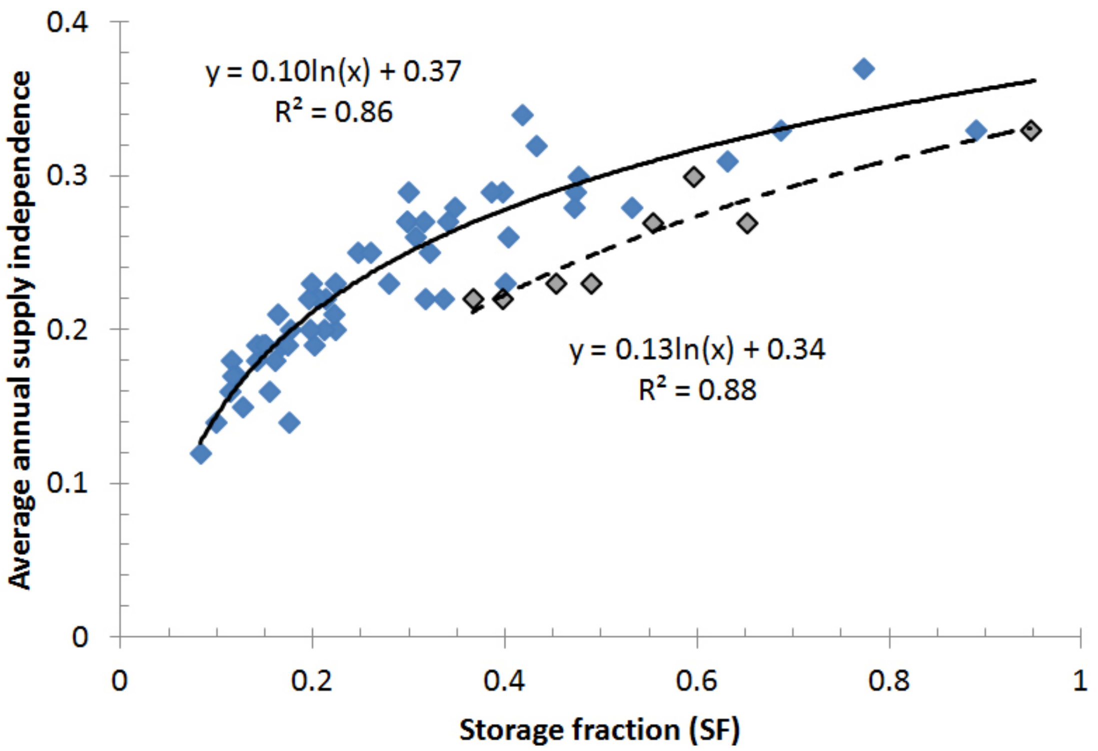


Fig. 9-6 Relationship between supply independence and storage fraction for simulated scenarios; leaking rainwater tank (**blue**) and conventional rainwater tank for base scenario only (**grey**).

The supply independence of a conventional rainwater tank appears to be consistently lower than the leaking tank. This occurs as only the volume of the water supply chamber and not the total tank volume is used in the regression of SF. Thus, the leaking tank achieves a higher storage efficiency, which should be expected when combining duties of water supply storage and runoff interception.

Finally, the supply independence for leaking rainwater tanks can be determined with reasonable confidence from (9-11) for potentially any location in Australia and for the range of design parameters studied in Chapter 8, noting that the volume of the water supply chamber is restricted to less than 8 kL.

$$SI = 0.01 \times \ln(SF) + 0.37 \qquad \textbf{(9-11)}$$

9.3.5 Dimensionless discharge fraction

Likewise regression confidence for the dimensionless discharge fraction was refined by iteratively adjusting the calibration factors for the demand fraction and standardised storage. The demand fraction factor was eliminated. Thus, the demand fraction and discharge fraction were combined. As expected a small factor was needed for the standardised storage. A constant environmental flow discharge of 200 L/d was adopted as the central range of discharges studied. Also, regression confidence was increased when the precipitation yield index was refined to just the capped daily precipitation. This suggests the distribution of daily rainfall is not significant in estimating of the potential environmental benefits of leaking rainwater tanks.

Finally, the calibrated discharge fraction can be determined with (9-12) and a reasonable regression confidence (R^2 = 0.80) was obtained to the environmental benefit index estimated from the scenarios studied in Chapter 8 (Fig. 9-7).

$$DF = {}^{100}\!/_{(A \times P_{cap})} \times \left({}^{D_r}\!/_{200}\right)^{0.4} \times \left({}^{V_t}\!/_{5}\right)^{0.3} \tag{9-12}$$

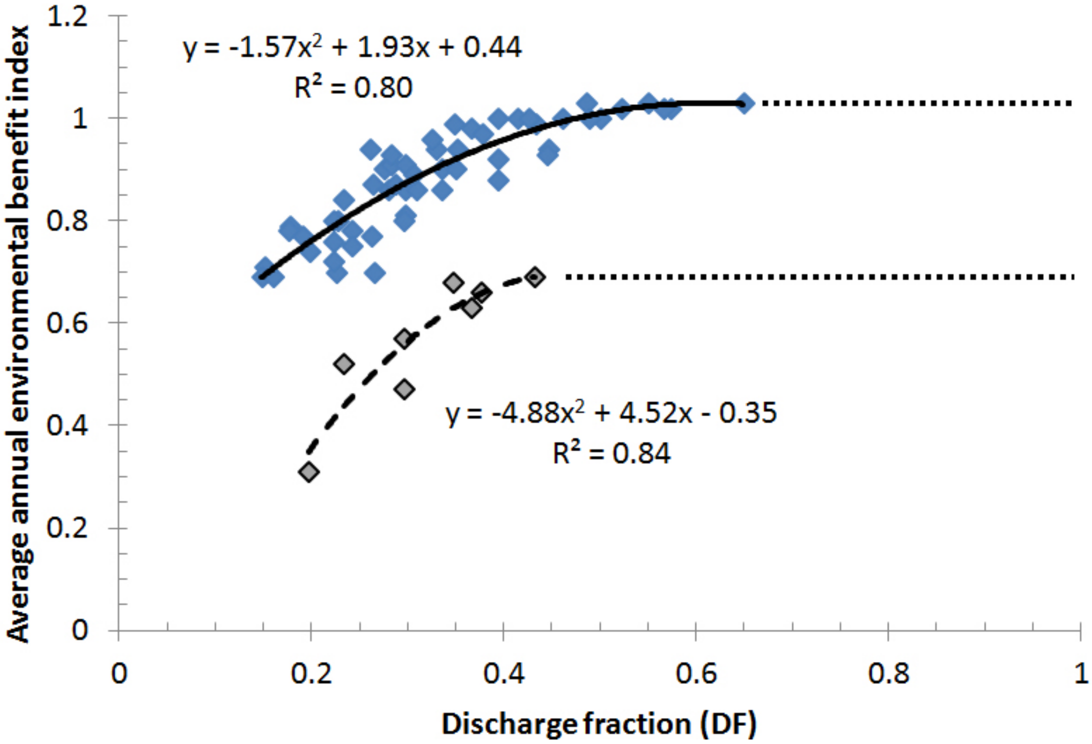


Fig. 9-7 Relationship between environmental benefit index and storage fraction for simulated scenarios; leaking rainwater tank (**blue**) and conventional rainwater tank for base case scenario (**grey**).

Thus, the environmental benefit index of leaking rainwater tanks can be determined with reasonable confidence from (9-13) for potentially any location in Australia and for the range of design parameters studied in Chapter 8.

$$EBI = \begin{cases} 1.0, & DF \geq 0.6 \\ -1.57 \times DF^2 + 1.93 \times DF + 0.44, & \text{otherwise} \end{cases} \tag{9-13}$$

9.4 Application of rapid performance estimation

Estimating the supply independence, environmental benefit index and volumetric utility of leaking rainwater tanks can be achieved by following the procedures previously described and summarised (Fig. 9-8).

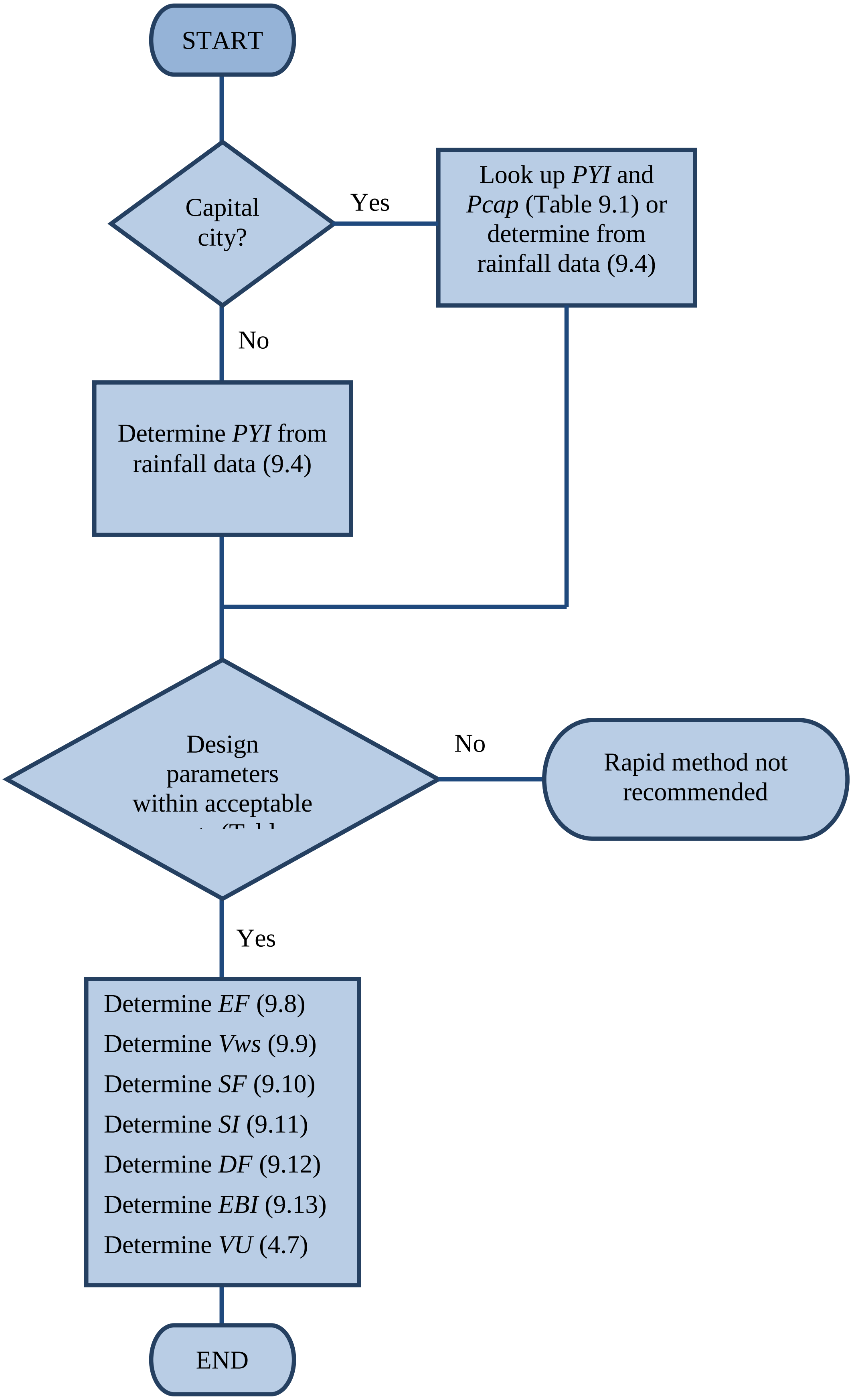


Fig. 9-8 Leaking tank rapid performance estimation flow chart

To demonstrate application of the rapid assessment procedure several locations were randomly selected where suitable daily rainfall observations were available (Table 9-3). The capped precipitation (9-1), ratio of precipitation days (9-2) and precipitation seasonality (9-3) was calculated to determine the precipitation yield indices (9-4) for the regional centres (Table 9-4). System design parameters were adopted (Table 9-5).

Table 9-3 Regional centres for rapid performance estimates

Site	Station	Rainfall observation period	Average annual rainfall (mm)
Coffs Harbour (NSW)	059040	1/3/1943 - 28/2/2013	1349
Geraldton (WA)	008051	1/3/1942 - 28/2/2013	440
Toowoomba (Qld.)	041529	1/3/1997 - 28/2/2013	740
Tweed Heads (NSW)	058056	1/3/1887 - 28/2/2013	1697
Urangan (Qld.)	040430	1/2/1970 - 31/1/2013	1082

Table 9-4 Precipitation yield indices of regional centres

Site	P_{cap} (mm/d)	R_{pd}	R_{ps}	PYI (mm/d)
Coffs Harbour (NSW)	2.10	0.24	0.65	0.99
Geraldton (WA)	1.02	0.16	0.84	0.25
Toowoomba (Qld.)	1.47	0.19	0.68	0.60
Tweed Heads (NSW)	2.51	0.28	0.64	1.25
Urangan (Qld.)	1.93	0.26	0.65	0.92

Table 9-5 System design parameters of regional centres

Site	Connected roof area A (m^2)	Household rainwater demand D_r (kl/y)	Total tank volume V_t (kL)
Coffs Harbour (NSW)	175	87	5
Geraldton (WA)	150	150	4
Toowoomba (Qld.)	100	87	2
Tweed Heads (NSW)	200	176	7
Urangan (Qld.)	150	87	5

The environmental flow release rates were estimated (Table 9-6) based on the capped precipitation and the step-wise linear equation (9.8). The volume of the water supply chamber was estimated (Table 9-6) using (9-9) being 50% of total storage for all sites excluding Geraldton, where linear interpolation was necessary across the lower range of parameter values stated in Table 9-2.

Table 9-6 Environmental release rate and water supply chamber volume of regional centres

Site	**Environmental flow release rate** $\boldsymbol{EF}$ **(L/day)**	**Percentage of tank for environmental flow chamber** $\boldsymbol{P_{EF}}$ **(%)**	**Water supply chamber volume** $\boldsymbol{V_{WS}}$ **(kL)**
Coffs Harbour (NSW)	175	50	2.5
Geraldton (WA)	100	60	2.4
Toowoomba (Qld.)	100	50	1
Tweed Heads (NSW)	200	50	3.5
Urangan (Qld.)	150	50	2.5

The supply independence was calculated (Table 9-7) from (9-11) using the storage fraction (9-10).

Table 9-7 Supply independence of regional centres

Site	**Storage fraction** $\boldsymbol{SF}$	**Supply independence** $\boldsymbol{SI}$
Coffs Harbour (NSW)	0.34	0.26
Geraldton (WA)	0.12	0.16
Toowoomba (Qld.)	0.09	0.14
Tweed Heads (NSW)	1.23	0.38
Urangan (Qld.)	0.27	0.24

The environmental benefit index was calculated (Table 9-8) from (9-13) using the discharge fraction (9-12).

Table 9-8 Environmental benefit indices of regional centres

Site	Discharge fraction DF	Environmental benefit index EBI
Coffs Harbour (NSW)	0.19	0.71
Geraldton (WA)	0.55	0.99
Toowoomba (Qld.)	0.37	0.88
Tweed Heads (NSW)	0.21	0.73
Urangan (Qld.)	0.25	0.77

Finally, the volumetric utility was determined for all regional centres from the average of SI and EBI (Table 9-9).

Table 9-9 Dual-duty performance of regional centres

Site	Supply independence SI	Environmental benefit index EBI	Volumetric utility VU
Coffs Harbour (NSW)	0.26	0.71	0.49
Geraldton (WA)	0.16	0.99	0.57
Toowoomba (Qld.)	0.14	0.88	0.51
Tweed Heads (NSW)	0.38	0.73	0.56
Urangan (Qld.)	0.24	0.77	0.50

9.5 Summary of rapid performance estimation

A rapid means of deriving the dual-duty performance of leaking and conventional rainwater tanks has been derived and demonstrated in a effort to increase the relevance of research results. The method is based on applying rainfall statistics that estimate the potential rainwater yield. Also, the method incorporates the main design parameters of rainwater systems including the connected roof area, tank volume and rainwater demand, which enables rapid performance assessment of alternate system designs.

Various regression equations were introduced to determined system performance and some design characteristics. The environmental flow rate can be determined from a step-wise linear relationship to the capped daily rainfall. The percentage of total tank storage to allocate to the environmental flow chamber is described based on the environmental flow rate and other design parameters. The supply independence is determined from a logarithmic relationship to a dimensionless storage fraction. The environmental benefit index is determined from a conditional polynomial relationship to a dimensionless discharge fraction.

With this rapid procedure the dual-duty approach to rainwater harvesting for conventional and leaking tank arrangements can be practiced without extended simulation and optimisation with UrbanTank. Consequently, a comprehensive planning tool is established which should facilitate the mainstream adoption of the dual-duty approach to rainwater harvesting.

Chapter 10 Conclusions and Recommendations

Chapter summaries and recommendations form the basis of the dissertation conclusions. The results of hypothesis testing are stated and the additional research questions are answered. The dissertation concludes by recommending future research to enhance the outcomes and promote dual-duty rainwater tanks to standard practice

10.1 Summary and conclusions

In Australia and abroad there is increasing interest in developing water sensitive cities, green cities, and spaces where we can maintain a vibrant and productive modern lifestyle that is considerate of, connected with and dependent on the environment. The humble rainwater tank has historically held a fundamental role in reducing the impact that metropolitan and regional centres place on contiguous water resources. It is now widely accepted that rainwater harvesting provides benefits beyond reducing the water demands of municipalities.

In this dissertation, the efficacy of rainwater tanks to restore aspects of stream hydrology which are degraded by urbanisation has been studied by simulation and volumetric analysis. A framework for assessing the dual-duty performance of rainwater tanks is introduced based on providing an alternate water supply while restoring degraded stream hydrology. This framework is intended to expedite the creation of water sensitive cities by promoting dual-duty rainwater tanks to standard practice.

Principally, the aim of this dissertation was to investigate various storage arrangements and methods of operating rainwater tanks to determine if environmental flows would increase dual-duty performance. The scope of research was not limited by the low-technology legacy of current practices. Investigated were adaptive approaches for enabling environmental flow releases that would necessitate technological advances to rainwater tanks that are not commonplace in the stormwater management industry. Also studied was the extent that environmental flows depletes rainwater supply; the extent that leaking rainwater tanks can improve stream flow hydrology in isolation to other stormwater management initiatives; the variation in dual-duty performance of rainwater tanks across the Australian spectrum of urban living; and methods to rapidly link dual-duty performance with system design parameters.

This dissertation has demonstrated the value of a dual-duty design emphasis for rainwater tanks and achieved the research objectives by introducing the UrbanTank mass-balance rainwater harvesting simulator; revealing the design parameters which greatly influence the performance of conventional and leaking rainwater tanks; linking outdoor water use with parsimonious climatic indices; applying measures of environmental benefit to rainwater tanks; supplementing archives of rainfall forecasts to allow long-term assessment of actuated environmental flows; studying dual-duty performance over the Australian spectrum of urban residential living; and establishing relationships between dimensionless storage fractions and the dual-duty performance of leaking rainwater tanks to facilitate rapid estimation of system design parameters and performance.

10.1.1 The UrbanTank rainwater simulator

The simulation of a rainwater tank and associated processes was deconstructed into four model components of catchment, water storage, water use and in the case of adaptive rainwater tanks, operating rules. Model artefacts of time-step, supply-spill sequence, catchment hydrology, and water use patterns were studied.

A six-minute time-step was applied for the catchment model to include rainfall intensity from pluviograph observations. The water storage and water use model components operated at an hourly time-step to increase the simulation processing efficiency. Operating rules were applied at daily intervals and environmental flow was enabled on the basis of the severity of daily rainfall forecasts and/or monthly rainfall statistics.

A spill-before-yield processing sequence was adopted to provide a conservative estimate of dual-duty performance. This sequence is presumed to underestimate rainwater yield and overestimate tank overflow. The magnitude of error was limited by the fine modelling time-steps adopted.

The catchment hydrology was defined by a review of parameter values for roof runoff and first flush diversion. A runoff coefficient of 0.9, daily initial loss of 0.4 mm and first flush depth of 0.4 mm was adopted in final simulation scenarios.

Hourly diurnal water use patterns for internal and outdoor cases were derived from the mean of measured values published in the literature. The household water use split between internal and external, and also between internal uses was derived from trends in component water use published in the literature. Central trends showed that household water use was 200 kL/y with 20% used outdoors. Rainwater demand scenarios were established based on various combinations of supplying toilet flushing, cold laundry taps, outdoor water use and total household water use.

Where possible model parameters were calibrated to independent research and the dimensions of the simulation scenarios were defined by the study sites (all Australian capital cities), roof area (100 m^2 to 200 m^2), average annual household rainwater demand (44 kL to 176 kL), tank volume (2.5 kL to 7.5 kL) and tank types (conventional, leaking and three adaptive approaches). Collectively, more than 150 unique simulations were analysed throughout the dissertation, most of which including historic observations of six-minute rainfall and daily maximum temperature for a duration of 30 to 90 years.

Simulation results were verified by three independent analyses. Results were consistent or conservative with PURRS simulation throughout Australia; consistent with statistical analyses and end use studies for South-East Queensland; but somewhat excessive when compared to field measurements from Sydney households. Overall, a reasonable verification of rainwater yield estimates from the UrbanTank simulator was provided. Thus, model simplifications and assumptions are valid.

10.1.2 What drives outdoor water use?

Seasonal or outdoor water use is the most difficult component to predict of residential demand. Studies have shown this component can vary significantly over the community cross-section but also temporally in response to seasonal change. Rainwater yield is reasonably sensitive to seasonal water use which necessitates a detailed study into what drives outdoor water use. The broad geographic scope of research prohibits application of water use models that are designed and calibrated for exclusive regions.

A single parsimonious model was introduced that predicts the monthly proportion of annual outdoor water use at various locations in Australia, from temperature and rainfall indices. The model showed a strong overall regression in studies where local calibration was eliminated thorough national regression of model parameters to climate statistics. The outdoor water use model was included in UrbanTank to qualify estimates of rainwater yield and dual-duty performance.

It was also discovered that the accuracy of mean monthly water use predictions generally increases as the number of years studied increases; predictions are generally weaker in studies taken after the millennium drought, which may suggest water use habits are changing and may become less sensitive to environmental factors; a temperature threshold at which outdoor water use is influenced is apparent in the studied locations; the water use sensitivity to rainfall varies by location and can be defined by a linear relationship to the standard deviation of daily rainfall; atypical water use patterns were the most difficult to predict and can occur in locations with non-seasonal rainfall; model parameters are expected to remain reasonably constant over time; the long-term annual variability in outdoor water use is less affected by changes in rainfall than temperature with the most stable annual patterns observed in locations with high annual rainfall variability; and the long-term monthly distribution of outdoor water use is estimated to closely follow the temperature index in most locations, except where winter rainfall is limited.

10.1.3 Quantifying environmental benefits of rainwater tanks

To promote the dual-duty performance of rainwater tanks the environmental benefits of harvesting roof water needs to be studied. In keeping with the scope of research, the study was limited to volumetric assessment and general hydrologic conditions of catchment. The practitioner is referred to Hamel *et al.* (2013) for further information on the salient drivers of urban stream baseflow.

The Environmental Benefit Index introduced by Walsh *et al.*(2010) was simplified for the research context. Simplifications included disregarding standardisation by impervious area, as this is unnecessary when the entire catchment is impervious; and disregarding the water quality sub-index, on the bases that overflow from rainwater tanks is not typically a significant source of pollution in urban stormwater. Furthermore, water quality assessment is beyond the research scope.

The water fluxes of leaking rainwater tanks were linked to the three remaining sub-indices of the simplified Environmental Benefit Index. The flow frequency sub-index is based on analysis of precipitation data and tank overflow and assesses compliance of runoff event frequency with natural hydrology. The volume reduction sub-index measures the capacity of rainwater tanks to retain excess runoff and comprises the water fluxes: *rainwater yield*, which is presumed to be diverted into the wastewater stream; *first flush*, which is recommended to discharge into an infiltration bed; and *rainfall runoff losses* from the roof catchment, as evaporation is returned to the atmosphere and other minimal losses are presumed to be absorbed by pervious catchments adjacent to the roof. Finally, the filtered flow volume sub-index assesses the compliance of environmental flow volume from rainwater tanks with filtered flows generated from natural catchments.

A dual-duty sensitivity analysis was conducted and suggested the research hypothesis may be valid, so far as dual-duty performance increased when environmental flows were released from rainwater tanks. However, given the high environmental benefits of leaking rainwater tanks it was unlikely that an adaptive approach to managing environmental flows would provide superior performance. Overall, the sensitivity analysis demonstrated high potential for dual-duty rainwater tanks.

10.1.4 Supplementing rainfall forecasts archives

One method proposed for enabling environmental flow from rainwater tanks was to establish a minimum water storage threshold, defined by the severity of rainfall forecasts. A high forecast severity corresponded to a low water storage threshold and a high probability that environmental flows would be enabled.

It is problematic to assess the long-term historic performance of a system which is dependent on the skill of current rainfall forecasting techniques. Problems exist in the limited duration of rainfall forecast archives and the decreasing skill of aging forecast records. Long-term assessment was essential to qualify the simulation results and to provide a comparative analysis with all other tank types and modes of operation.

Several methods for supplementing rainfall forecasts archives were studied including training artificial neural networks to match the residual errors discovered in hindcasts; a behavioural method which analysed and replicated the errors of rainfall forecasts by creating statistical representation of the modes of failure; and two other methods of randomly applying residual errors to rainfall observations based on Gaussian distribution and percentile error.

Point observations of rainfall were compared to gridded rainfall forecasts at single points for each Australian capital city, for horizons up to four days and mean accumulation periods up to eight days. Generally the highest forecast skill occurred for the shortest horizon and the longest mean accumulation period, with some locations showing a skill reduction beyond a mean accumulation period of three days. Overall, the rainfall forecasts had moderate skill but this may be conservative given the limited study scope.

The behavioural method for supplementing archives of rainfall forecasts was superior to all other methods studied. Long-term time-series of daily synthetic rainfall forecasts were generated where the skill was statistically similar to current forecasts by several measures of accuracy. These synthetic forecasts were included in the long-term assessment of adaptive rainwater tank that release environmental flows based on forecast severity.

10.1.5 Dual-duty performance in Australian cities

An overall picture of the potential dual-duty performance of conventional, leaking and adaptive rainwater tanks was provided by studying a base scenario in all capital cities. The volumetric utility of leaking and adaptive approaches was consistently superior to conventional rainwater tanks. Also, the adaptive approaches showed no discernible advantage over the simpler leaking tank. Similar results were discovered for the supply independence, environmental benefit index, water balance and additional statistics studied.

Some behavioural differences of leaking and adaptive rainwater tanks were: A slight increase in the environmental benefit index with adaptive systems that respond to rainfall forecasts; adaptive approaches were generally better at preserving rainwater yield; adaptive approaches generally reduced the longest annual duration without environmental flows but also reduced the longest duration with environmental flow; and environmental flow with adaptive approaches is more intermittent, which is not typical of natural hydrology. Therefore, the added complexity of adaptive approaches is not justified by significant improvements in performance. Consequently, further investigations were refined to conventional and leaking rainwater tanks.

The performance assessment was extended to consider the spectrum of urban living in Australia. Mixed results were found for the optimum environmental flow chamber volume. When roof area was altered, a positive correlation was evident in sites with a dominant rain season. In other sites there was either no change or a negative correlation, as excessive environmental flow volumes needed to be mitigated. Also, the optimum chamber volume is positively correlated to total tank volume and rainwater demand in all study sites.

An assessment of urban density showed that the optimum environmental flow chamber volume is negatively correlated to urban density, as is the dual-duty performance. This does not suggest a hydrologic economy of scale exists but rather the larger rainwater demand and tank volume that is typical in low urban density development is beneficial for dual-duty rainwater tanks.

10.1.6 Rapid dual-duty performance estimation

To increase the relevance of the research results it was recommended that a rapid method be developed for linking dual-duty performance to system parameters and rainfall statistics. It is well-known that annual average rainfall is poorly correlated to rainwater yield for reasons that introduce bias including seasonality of rainfall and excessive daily rainfall. A precipitation yield index was introduced based on statistical representations of the three modes of either failure or lost opportunity of rainwater tanks: (1) empty and unable to meet demand, from an extended period of low or no rainfall; (2) sudden overflow and unable to increase yield, from a single large rain event; and (3) continuous overflow from continuous or near continuous rainfall over a rain dominant period.

A reasonable correlation (R^2 = 0.92) between rainwater yield and the precipitation yield index was demonstrated for the leaking tank, base scenario and all capital cities. A storage fraction was introduced which included the precipitation yield index and dimensionless relationships were established for supply independence. A reasonable correlation (R^2 = 0.84) was provided for all scenarios studied.

Similarly, a discharge fraction was introduced which included the capped precipitation and dimensionless relationships were established for environmental benefit index for all scenarios included in the dual-duty performance assessment. A reasonable correlation (R^2 = 0.80) was provided.

Also a step-wise liner relationship was established between the capped precipitation and the environmental flow release rate. It was however stated that in practice the permeability of soil should be also considered to ensure that environmental flows do not exceed the practical limits of local soil conditions.

A discussion was given for how to estimate the optimum volume of the environmental flow chamber, in absence of a determined relationship. This guidance removes the necessity to run optimisation routines in the UrbanTank software.

The dissertation results conclude with three simple performance charts for leaking and conventional rainwater tanks. The charts allow rapid estimation of the key performance metrics included in the dissertation. The charts include the scope of parameter values studied and rainfall statistics that can be derived potentially from any location in Australia and for many similar climates abroad.

Thus, the research hypothesis that dual-duty performance can be improved by allowing environmental flows from rainwater tanks is valid and thoroughly tested throughout typical urban residential settings in Australia. The presumption that an adaptive approach for enabling environmental flows would be superior was false. This is a desirable outcome as dual-duty rainwater tanks can be promoted to standard practice with minimal change and added cost to the status quo. Also, the presumption that rapid methods could be established for deriving dual-duty performance was true.

The additional research questions have also been answered. The extent that rainwater supply independence was reduced when enabling environmental flows was approximately 2% for the scenarios tested. This is a desirable result considering the average increase in environmental benefit was 33% and in some scenarios the benefit more than doubled.

Other WSUD components would be needed in addition to leaking rainwater tanks if the connected roof area does not constitute the large majority of impervious area of the allotment and if roof contaminants are high and water quality is unsuitable for discharge into the drainage system.

The dual-duty performance for leaking rainwater tanks can vary throughout Australia and sites with dominant rain seasons are in the lower bracket of results. Otherwise, results are highly desirable for southern states and in Queensland results are also reasonable.

10.2 Recommendations for further research

This dissertation covers a broad assessment of the volumetric performance of a variety of rainwater tanks and operating methods, supplemented by studies of water use and rainfall forecasts. However not all aspects of research could be included within the dissertation scope and recommendations for further research are necessary.

It was reported that roof runoff coefficients may display a non-linear correlation to rainfall intensity and model estimates of dual-duty performance are particularly sensitive to this coefficient. Therefore, further research is recommended to define this relationship.

Further research is recommended for the outdoor water use model to improve validation at sites with higher standard deviations of daily rainfall, supported by calibration with measured water use at finer resolutions of daily or weekly timescales. Measured data prior to, during and after the millennium drought should also be applied to verify whether water use habits have changed in response to water conservation programs, and whether model parameters change with time.

The occurrence of baseflow is dependent on complex relations to catchment characteristics including topography, soils, land use and climate. It is recommended that the general relationships provided in this dissertation are reinforced by greater examination of the behaviour of baseflow in catchments of particular interest to the practitioner.

The performance of adaptive rainwater tanks, which utilise rainfall forecasts, could have been improved by additional assessment of forecast skill. It is recommended that further research is conducted to quantify the skill of rainfall forecasts by including additional pluviograph stations that surround forecast grid points and removing the bi-linear downscaling of gridded forecasts.

Dimensionless relationships to derive the optimum environmental flow chamber volume were not established. These relationships would improve the statistical methods for rapid performance estimation. Additional scenarios should be tested to extend the range of parameter values that are valid for these dimensionless relationships.

Field measurements of leaking rainwater tanks should be conducted to confirm the simulation results from UrbanTank. Case studies should be investigated to demonstrate the application of leaking rainwater tanks to improve stream hydrology in specific urban catchments.

Finally, economic evaluation of rainwater tanks should be revised to include their dual-duty benefits. The value of rainwater tanks is significantly more than simply an alternate water supply.

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Appendix A Gridded rainfall forecast performance - Additional metrics and contingency thresholds

Results of additional rainfall forecast performance metrics for Australian capital cities for the period of 2008-2010.

LIST OF FIGURES

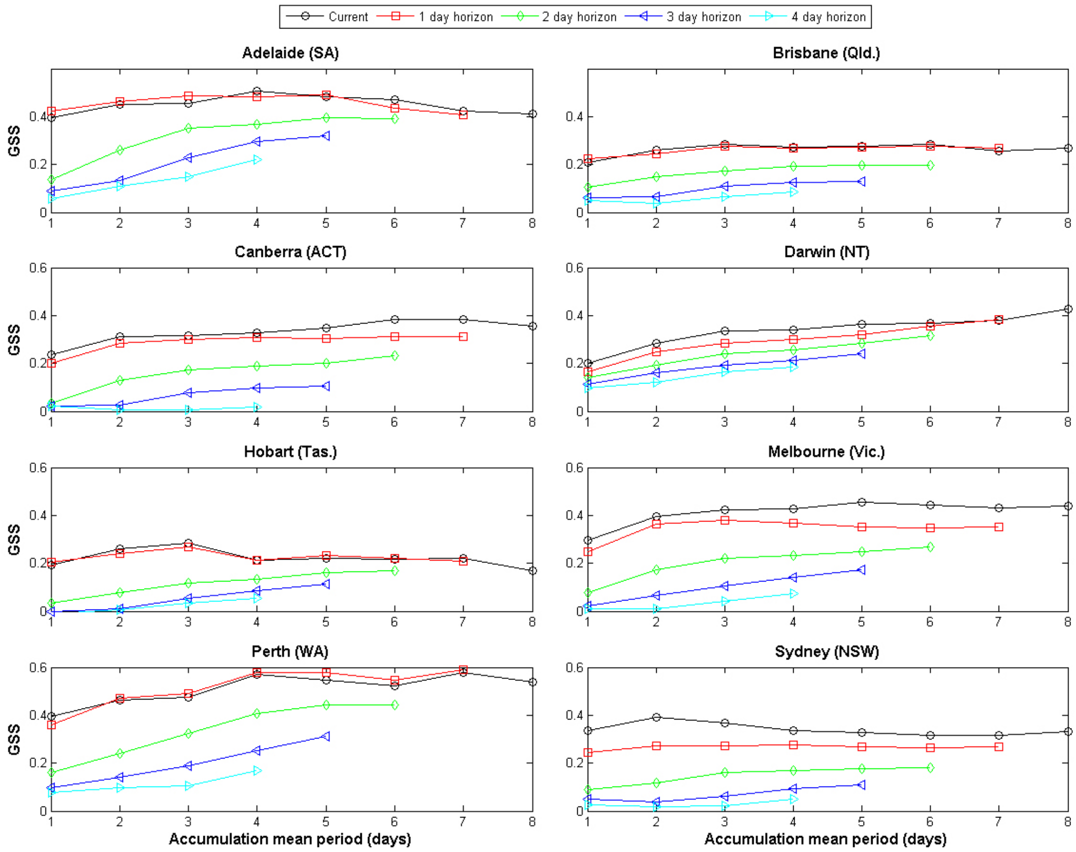

Fig. A-1 GSS of gridded forecasts for 0.25 mm/d contingency threshold.

Marginal change in peak skill score is observed when compared to the 0.5 mm/d threshold adopted within the analysis including: (1) Noticeable peak now also occurs in Adelaide; (2) Higher skill observed in Brisbane; (3) Lower skill observed in Canberra and Sydney; and (4) Peak occurs earlier in Sydney.

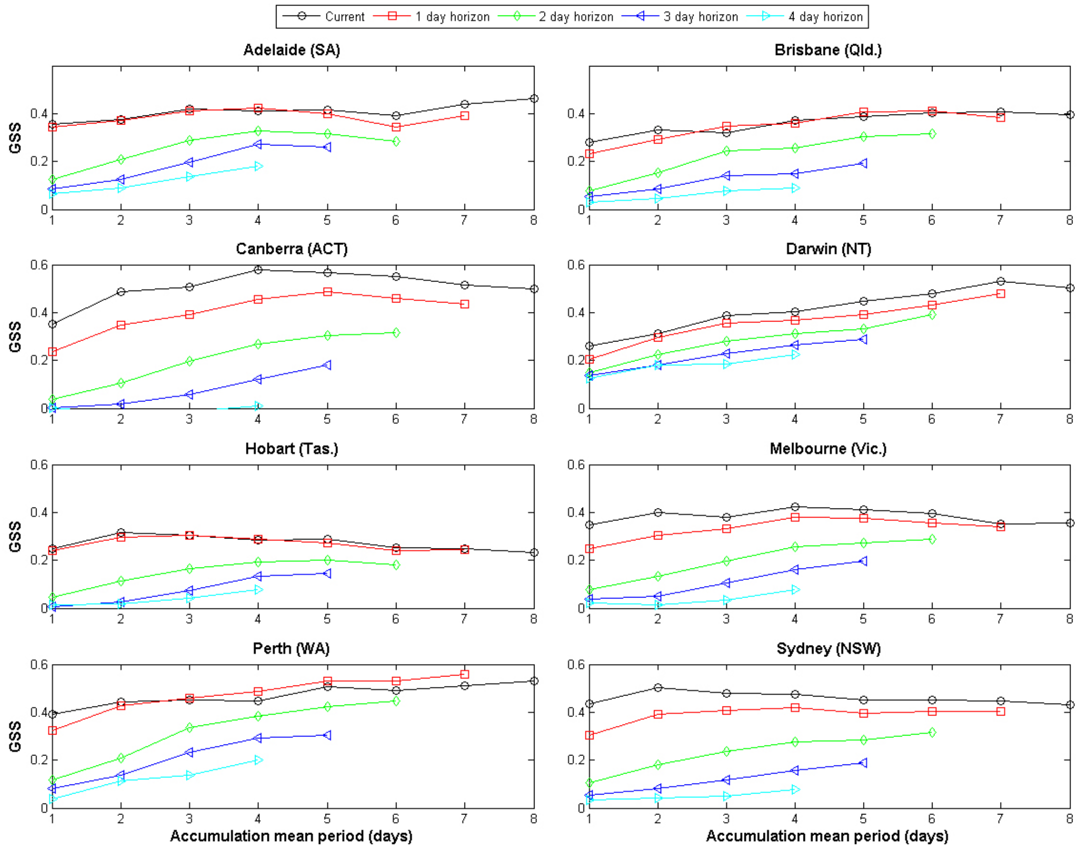

Fig. A-2 GSS of gridded forecasts for 0.75 mm/d contingency threshold.

Marginal change in peak skill score is observed when compared to the 0.5 mm/d threshold adopted within the analysis including: (1) Noticeable peak now also occurs in Canberra and Melbourne; and (2) Peak occurs earlier in Hobart and Sydney.

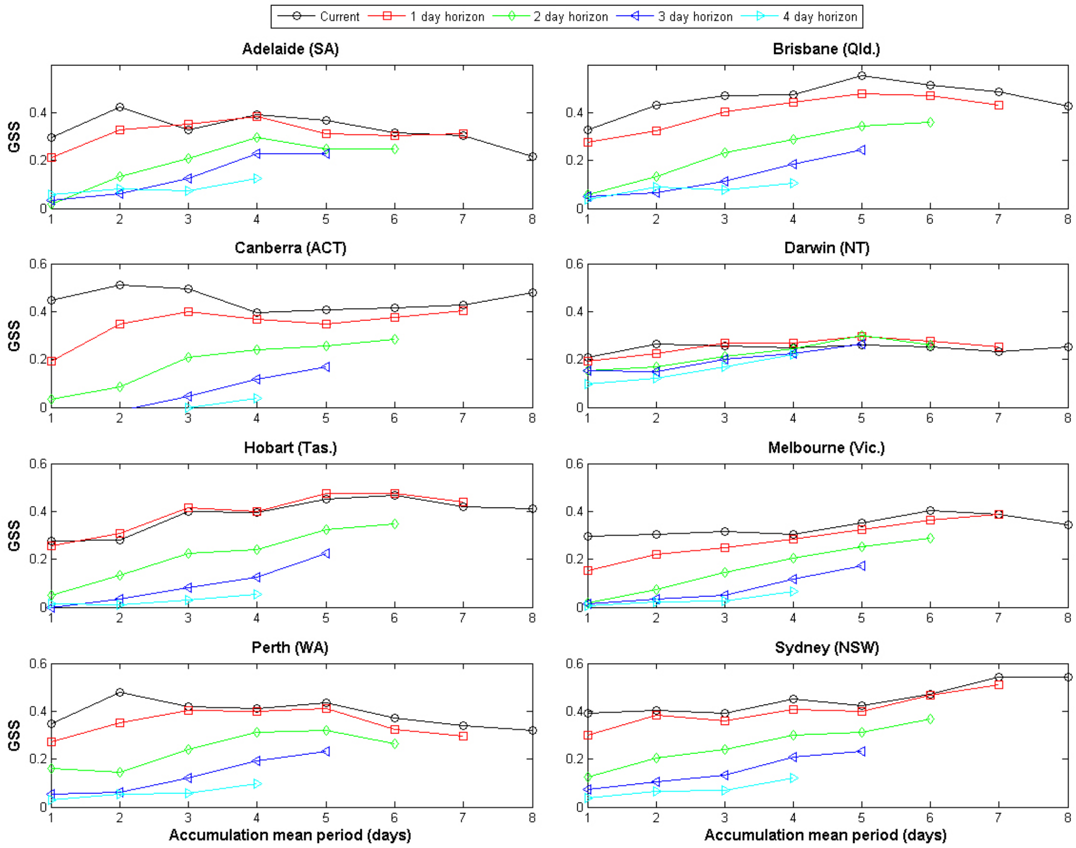

Fig. A-3 GSS of gridded forecasts for 2.5 mm/d contingency threshold.

Marginal change in peak skill score is observed when compared to the 0.5 mm/d threshold adopted within the analysis including: (1) Noticeable peak now also occurs in Adelaide, Brisbane and Perth; (2) Higher skill observed in Brisbane, Hobart and Sydney; (3) Unusual curve observed in Canberra which suggests multiple peaks may occur; (4) Peak occurs earlier in Perth; and (5) Peak no longer definitively shown for Sydney.

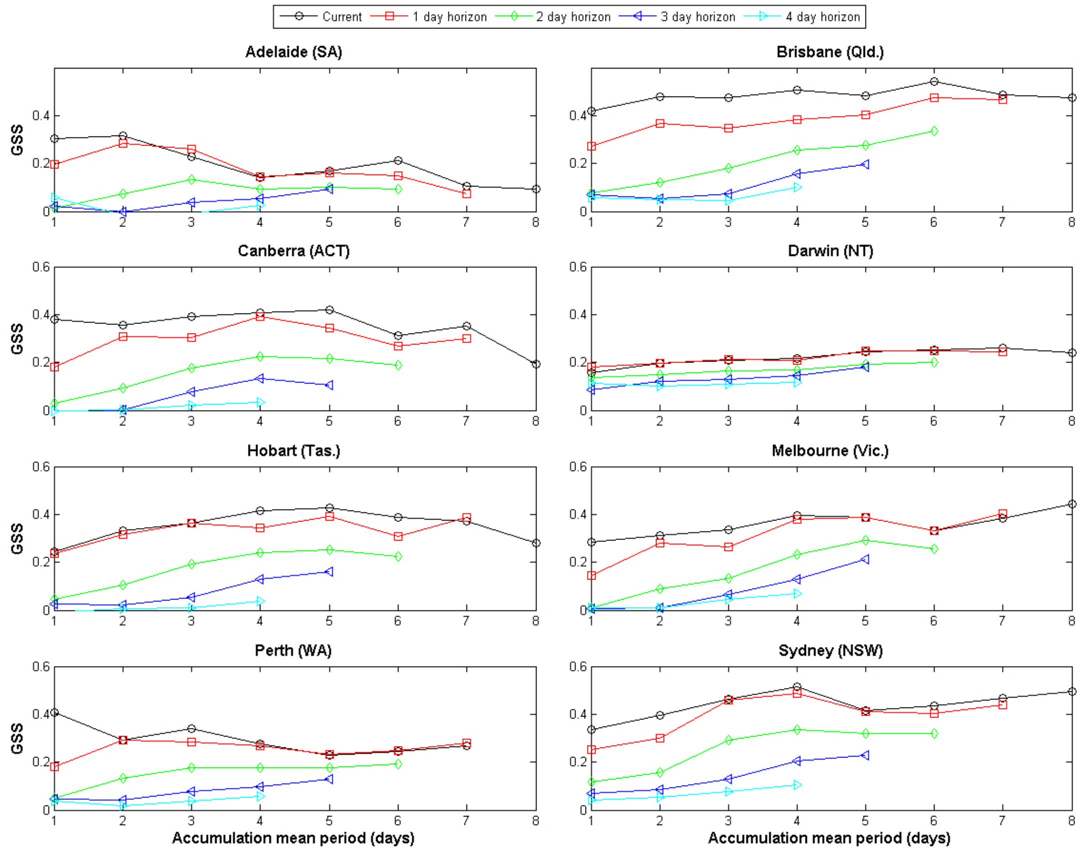

Fig. A-4 GSS of gridded forecasts for 5.0 mm/d contingency threshold.

Marginal change in peak skill score is observed when compared to the 0.5 mm/d threshold adopted within the analysis including: (1) Noticeable peak now also occurs in Darwin; (2) Higher skill observed in Brisbane, Hobart and Sydney; (3) Unusual curve observed in Melbourne and Sydney which suggests multiple peaks may occur; (4) Peak occurs very earlier in Adelaide and Perth; and (5) Lower skill in Adelaide, Canberra, Darwin and Perth

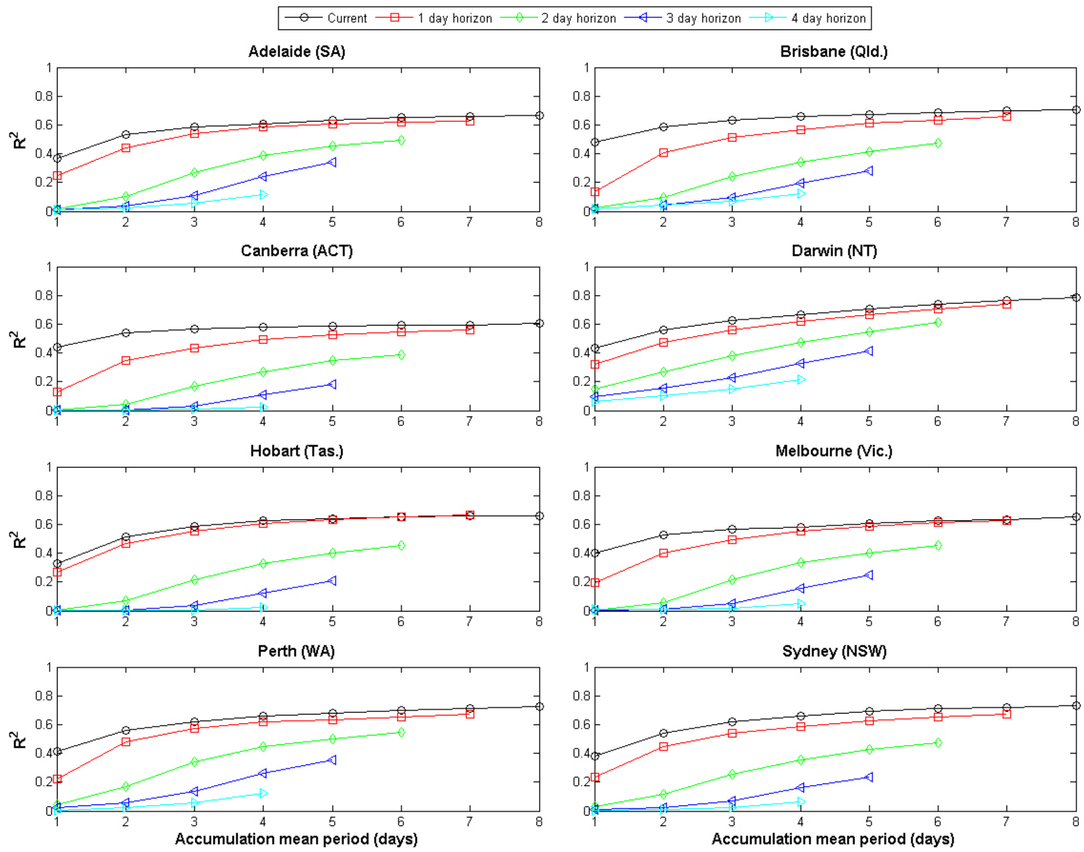

Fig. A-5 R^2 of gridded forecasts for Australian capital cities.

By coefficient of determination the peak performance is not discovered within the scenarios studied in all locations. Maximum and minimum correlations are similar for all locations and consistently relate to forecast time horizon and accumulation period. The main shortcoming of this metric is no capacity to consider the number of random hits expected due to chance. This is the reason peak performance is not discovered.

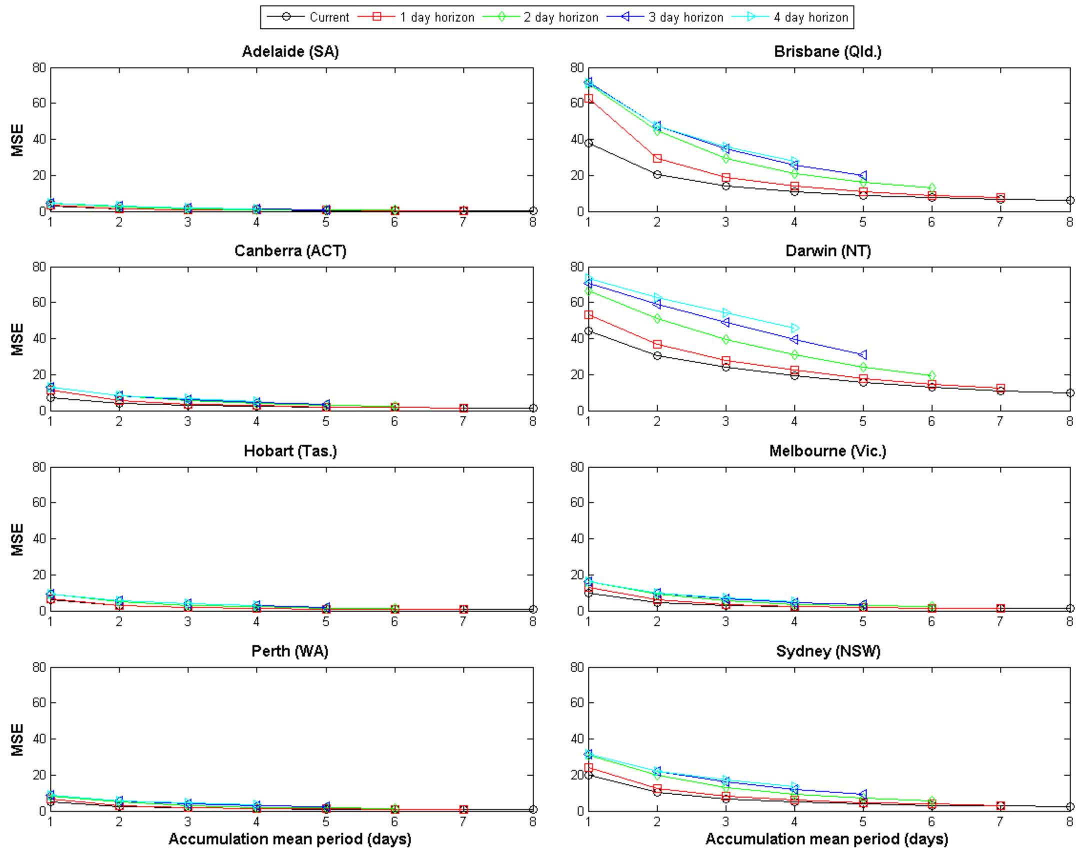

Fig. A-6 MSE of gridded forecasts for Australian capital cities.

Similar to the coefficient of determination, errors are shown to reduce as the accumulation period increases and as the forecast time horizon reduces. The magnitude of errors is significantly biased in sites which experience high intensity rainfall. This is the main shortcoming of this metric.

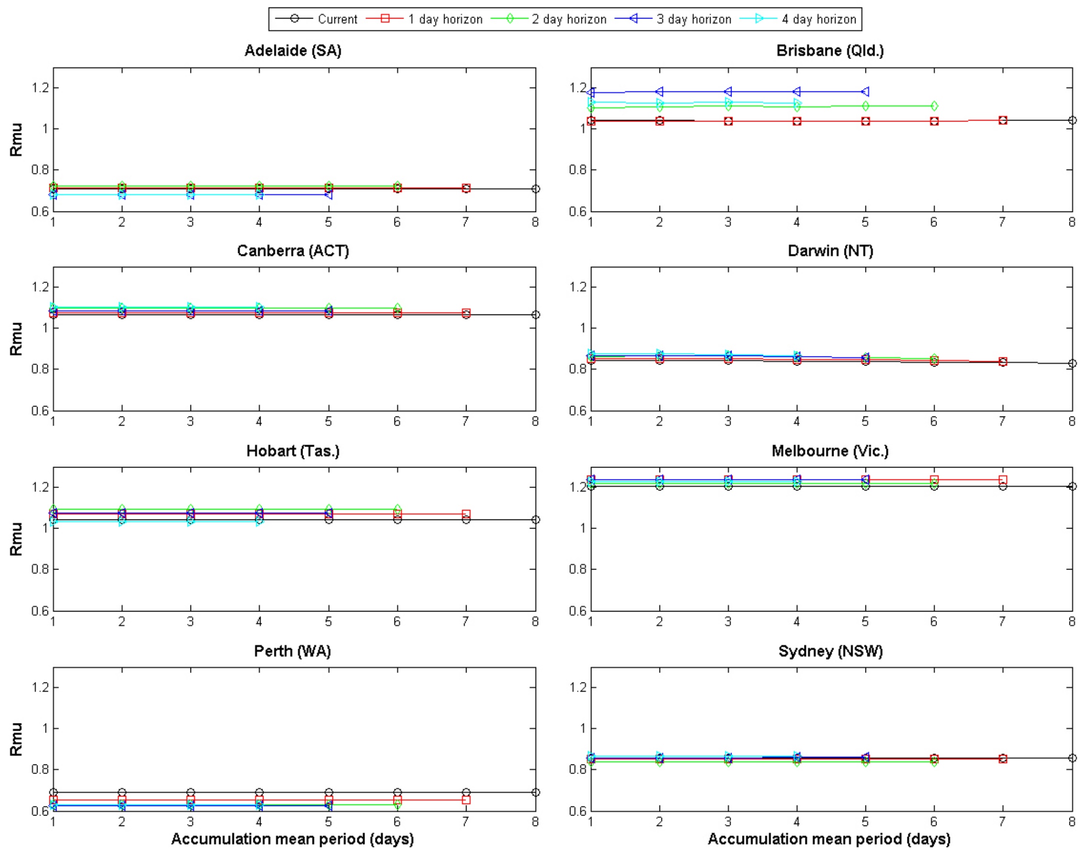

Fig. A-7 Rmu (ratio of mean values) of gridded forecasts for Australian capital cities.

By the study of the ratio of mean forecast to mean rainfall observations there is little difference in forecast skill over the accumulation periods and forecast time horizons studied. With few exceptions, the forecast for the current day offers ratios closest to unity, which is a desirable results.

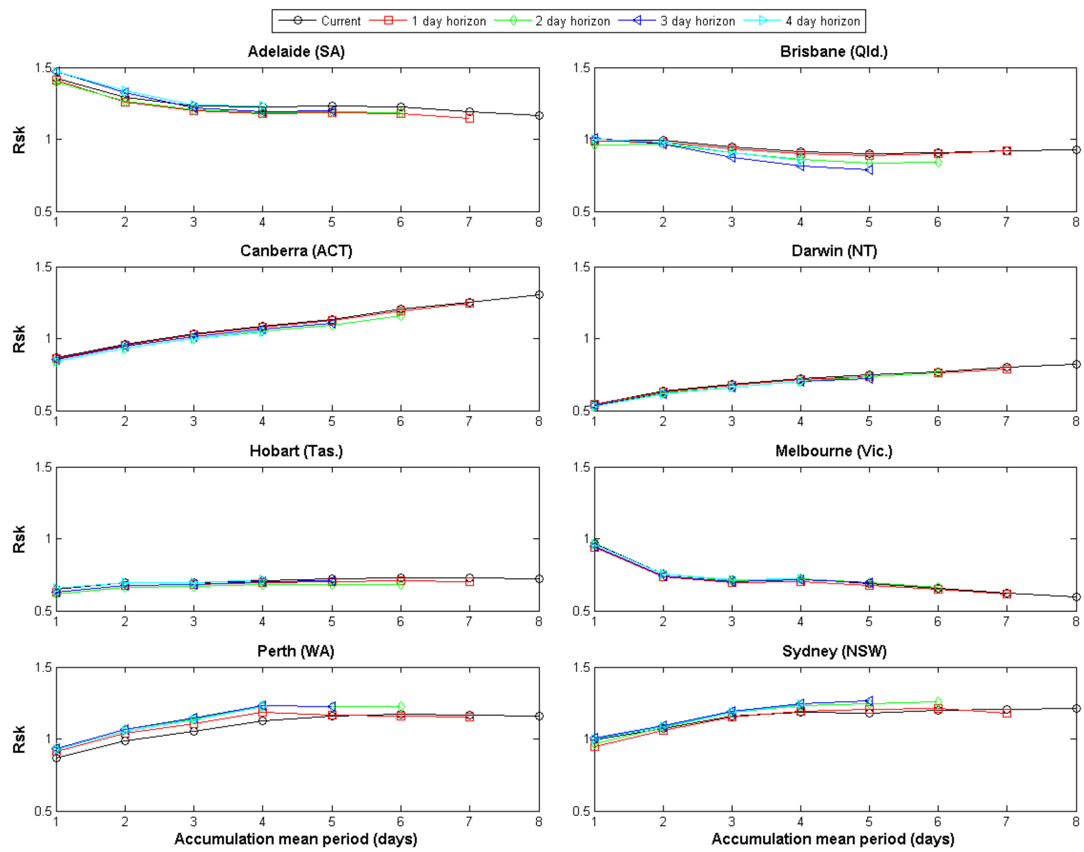

Fig. A-8 Rsk (ratio of skewness) of gridded forecasts for Australian capital cities

By the study of the ratio of forecast skewness to rainfall observation skewness there is little difference in forecast skill for the various forecast time horizons. However, the ratio is sensitive to the accumulation period. A ratio of one is the desired result. Some locations achieve greater skill over the accumulation period (Adelaide, Darwin and Hobart). Others decrease in skill over the accumulation period (Melbourne, Perth and Sydney). In some locations (Brisbane, Canberra and Perth) a desirable result is found for a two day mean period but beyond this forecast skill usually reduces. No discernible relationship to study location could be obtained.

Appendix B Additional results from ANN, Gaussian and PMC models to supplement rainfall forecast archives

Results of additional models for 2008 and for all Australian capital cities.

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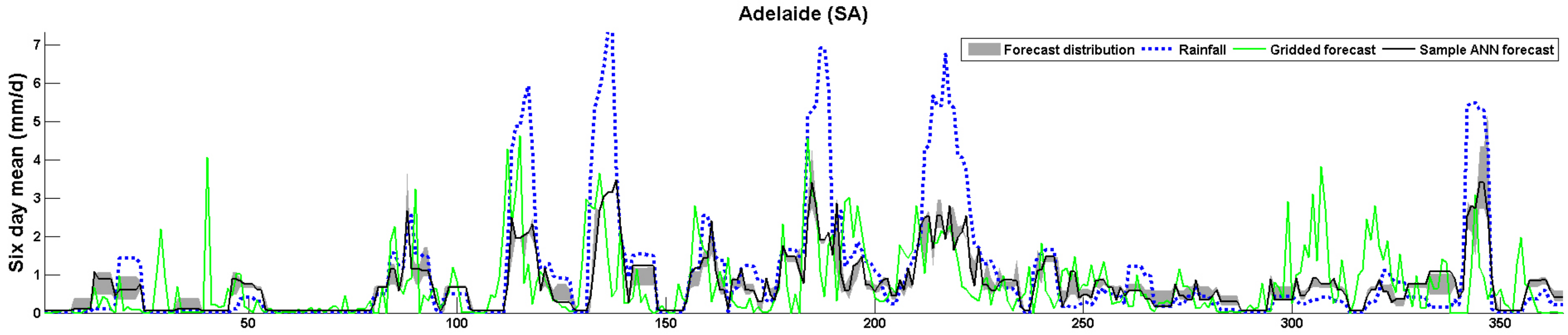

Fig. B-1 ANN rainfall estimates for 2008 in Adelaide.

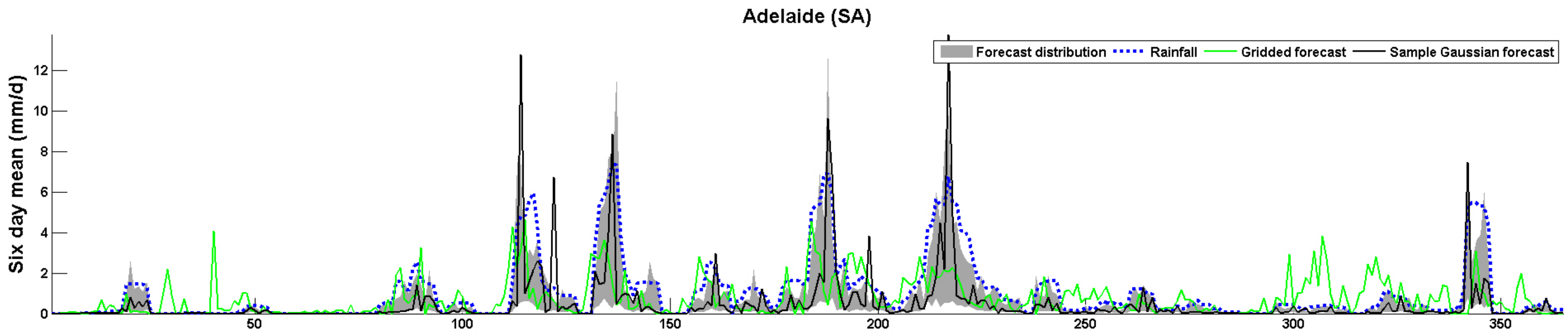

Fig. B-2 Gaussian rainfall estimates for 2008 in Adelaide.

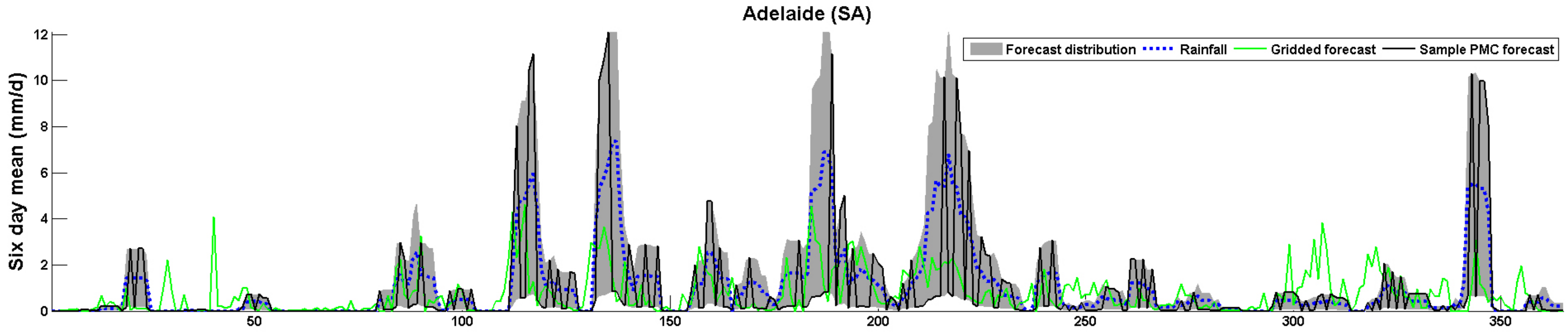

Fig. B-3 PMC rainfall estimates for 2008 in Adelaide.

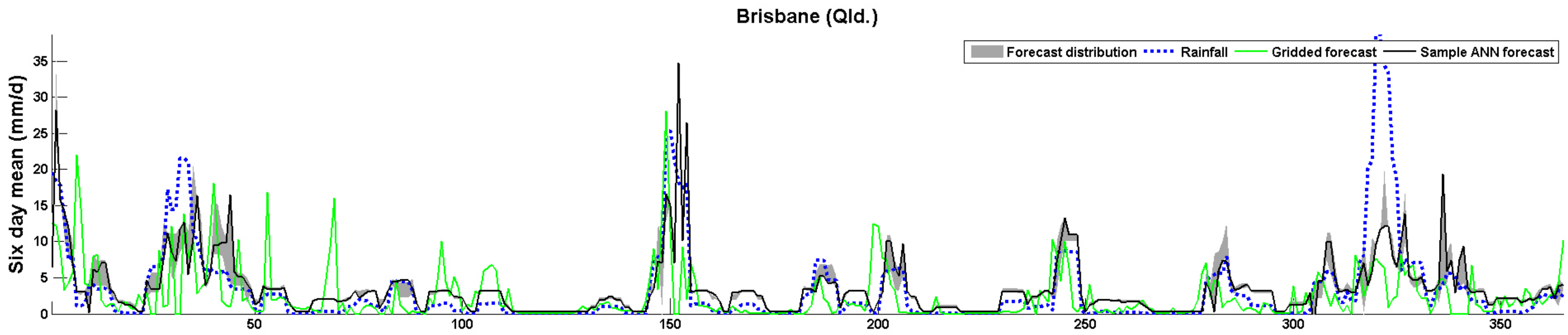

Fig. B-4 ANN rainfall estimates for 2008 in Brisbane.

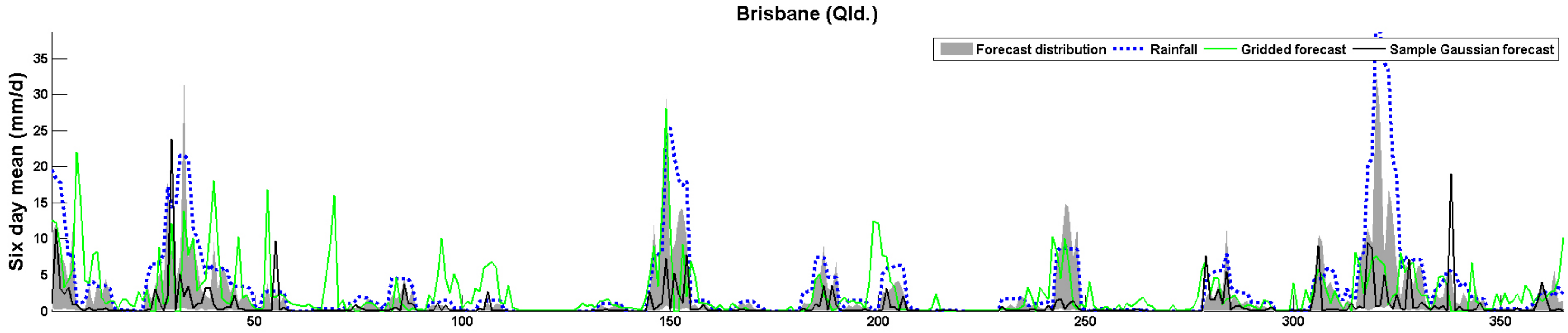

Fig. B-5 Gaussian rainfall estimates for 2008 in Brisbane.

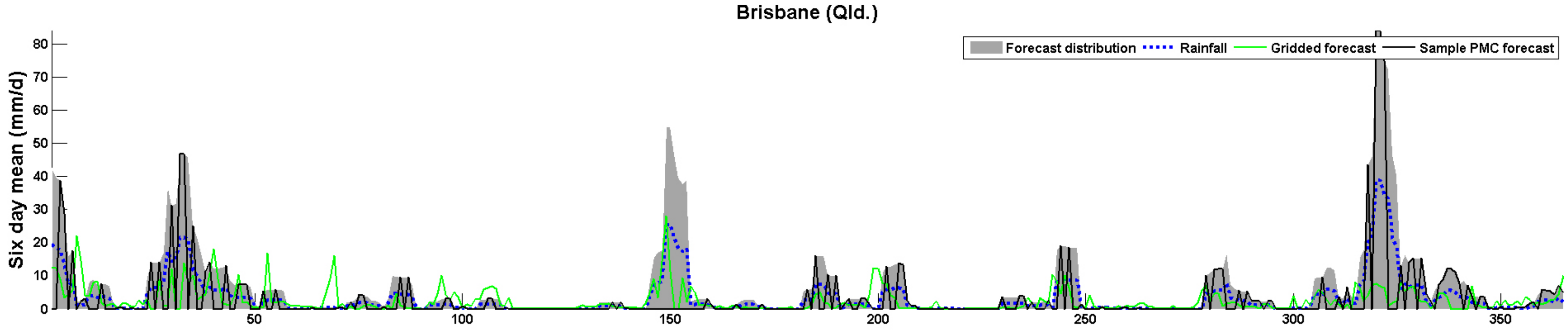

Fig. B-6 PMC rainfall estimates for 2008 in Brisbane.

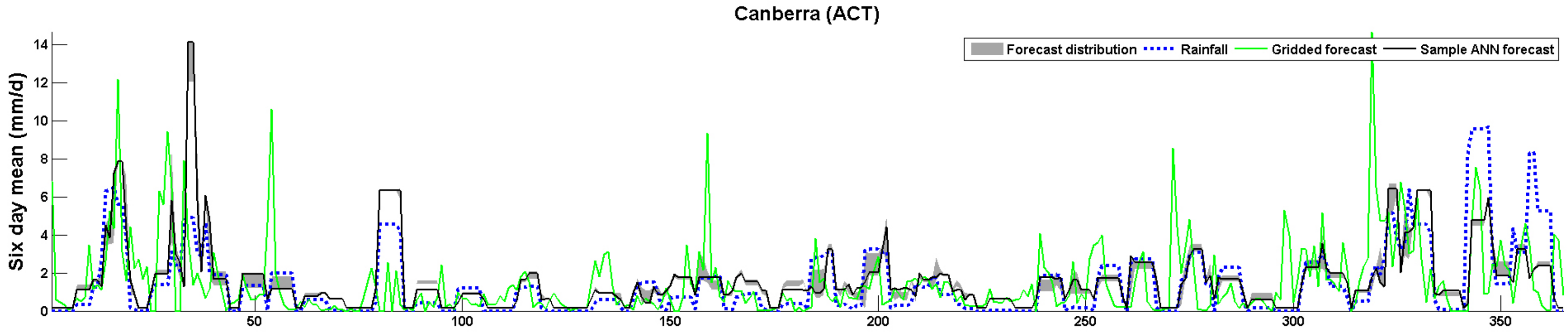

Fig. B-7 ANN rainfall estimates for 2008 in Canberra.

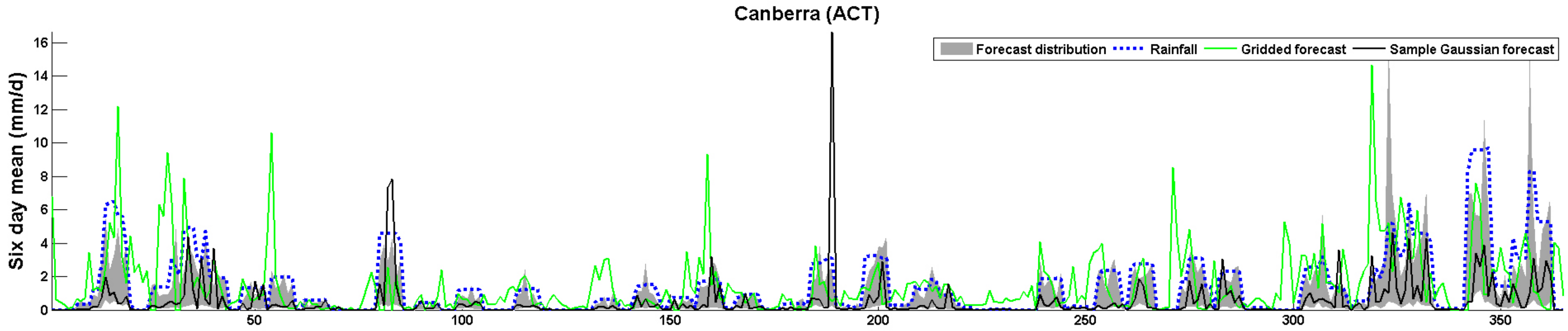

Fig. B-8 Gaussian rainfall estimates for 2008 in Canberra.

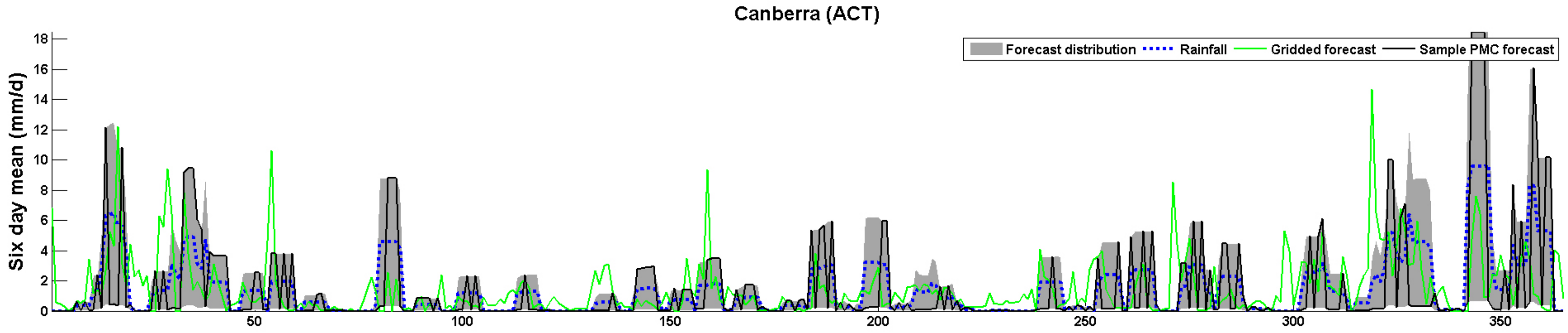

Fig. B-9 PMC rainfall estimates for 2008 in Canberra.

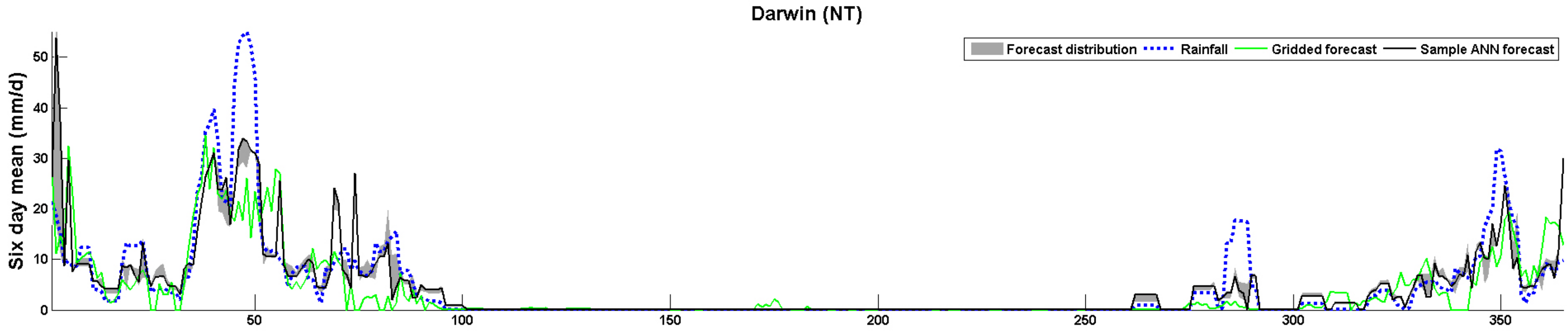

Fig. B-10 ANN rainfall estimates for 2008 in Darwin.

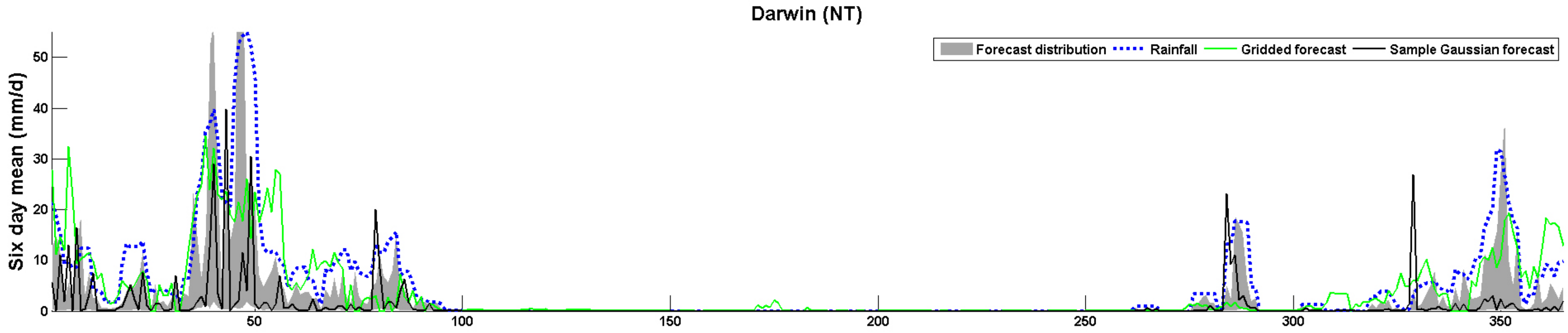

Fig. B-11 Gaussian rainfall estimates for 2008 in Darwin.

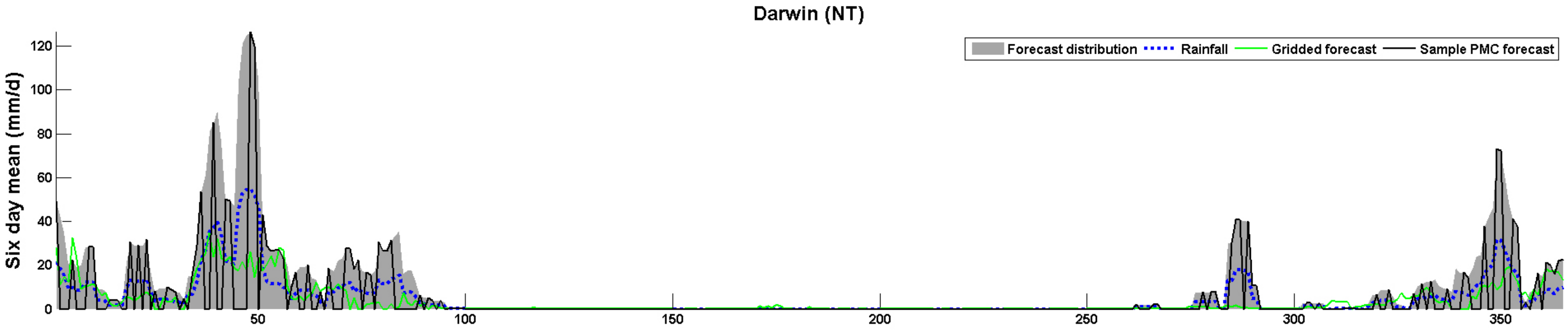

Fig. B-12 PMC rainfall estimates for 2008 in Darwin.

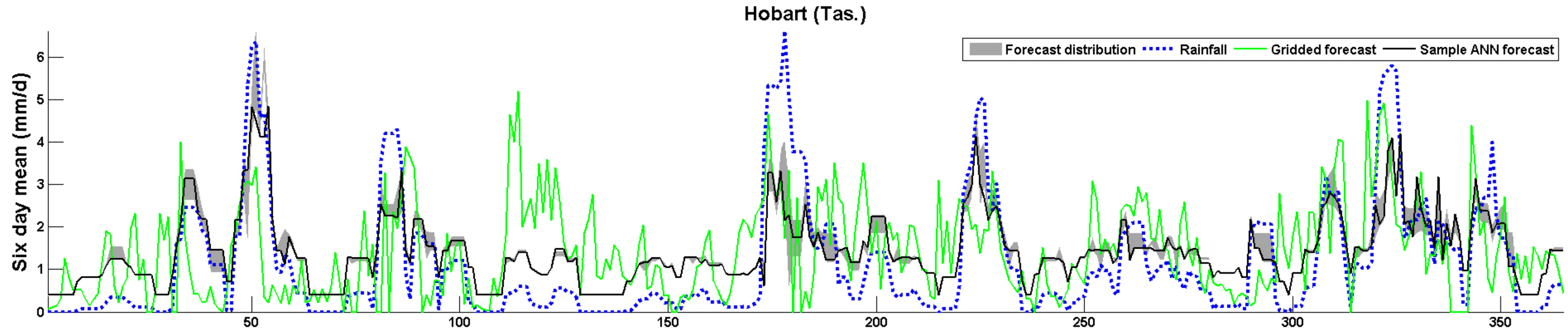

Fig. B-13 ANN rainfall estimates for 2008 in Hobart.

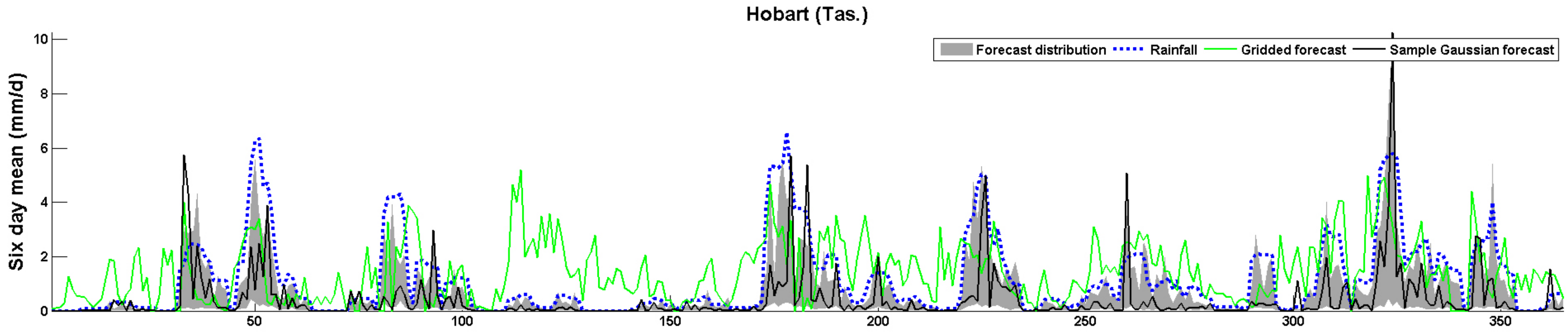

Fig. B-14 Gaussian rainfall estimates for 2008 in Hobart.

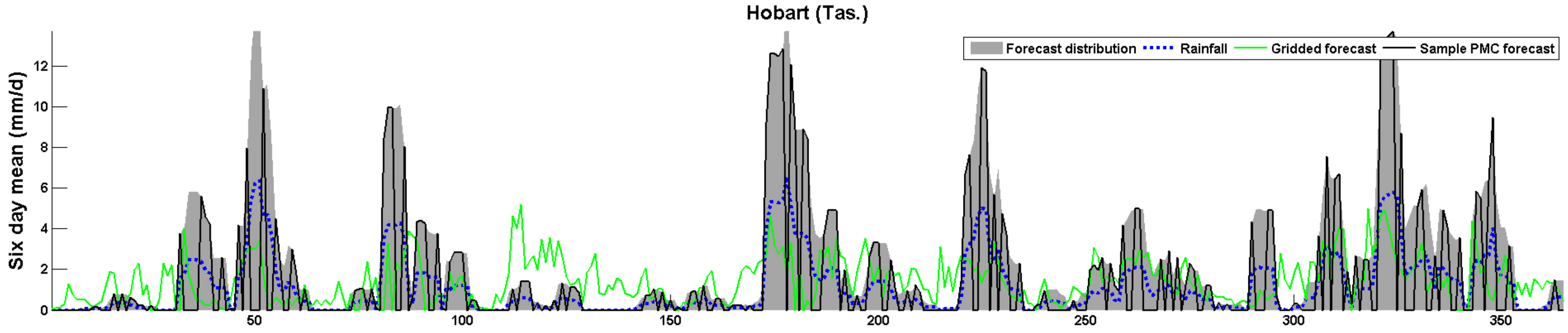

Fig. B-15 PMC rainfall estimates for 2008 in Hobart.

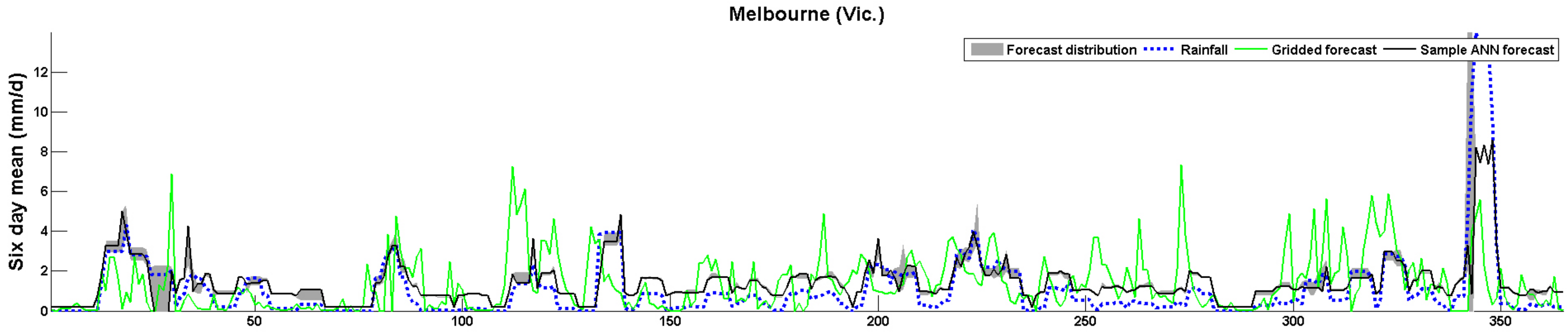

Fig. B-16 ANN rainfall estimates for 2008 in Melbourne.

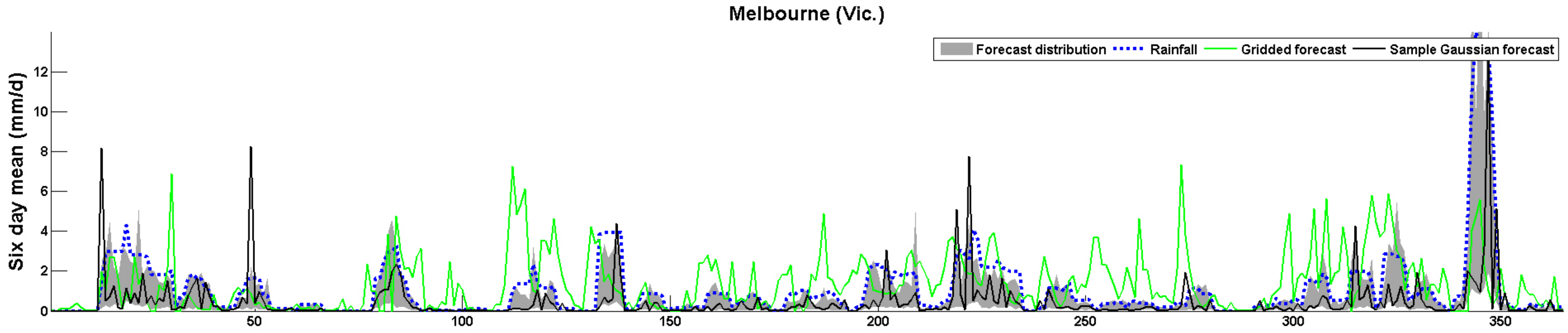

Fig. B-17 Gaussian rainfall estimates for 2008 in Melbourne.

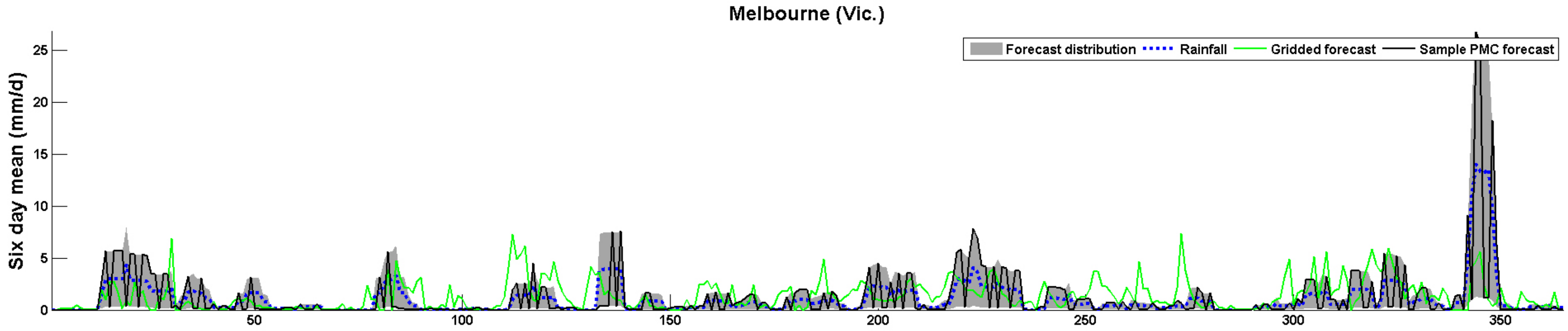

Fig. B-18 PMC rainfall estimates for 2008 in Melbourne.

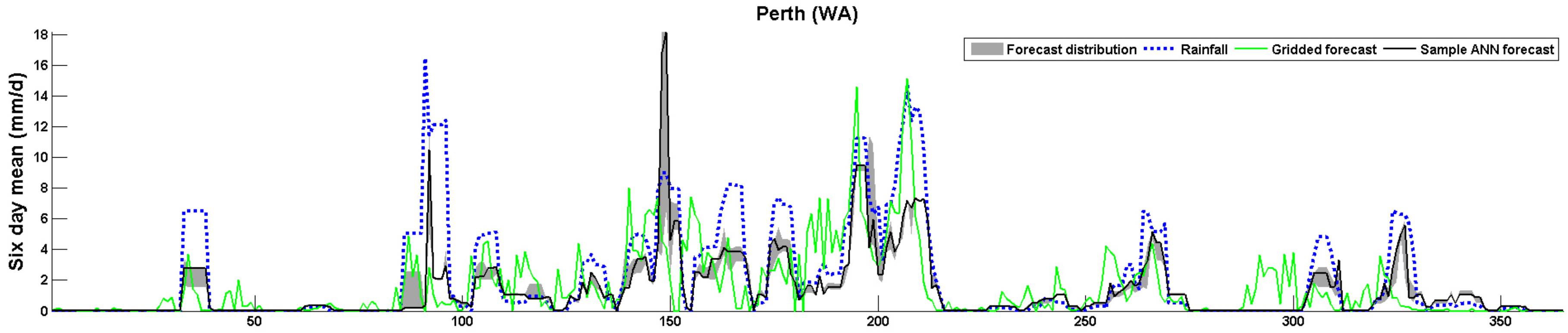

Fig. B-19 ANN rainfall estimates for 2008 in Perth.

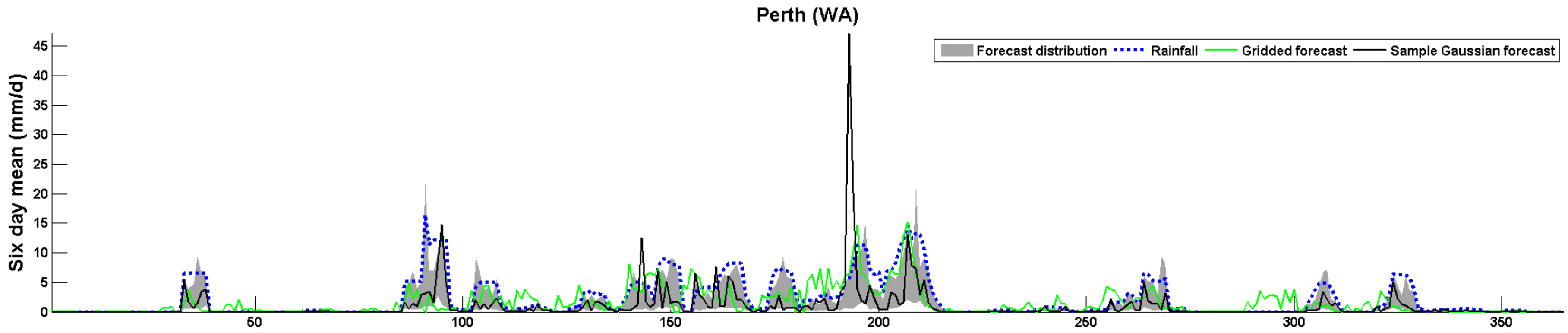

Fig. B-20 Gaussian rainfall estimates for 2008 in Perth.

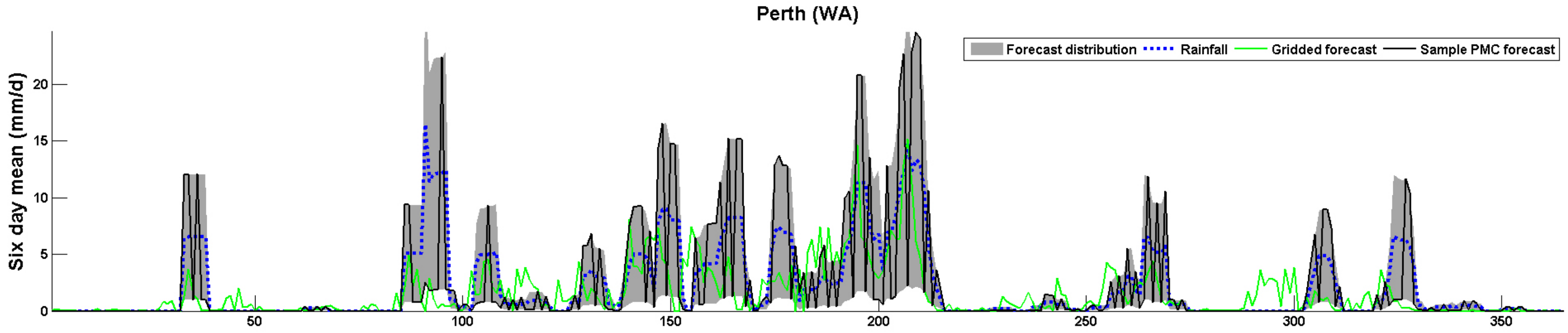

Fig. B-21 PMC rainfall estimates for 2008 in Perth.

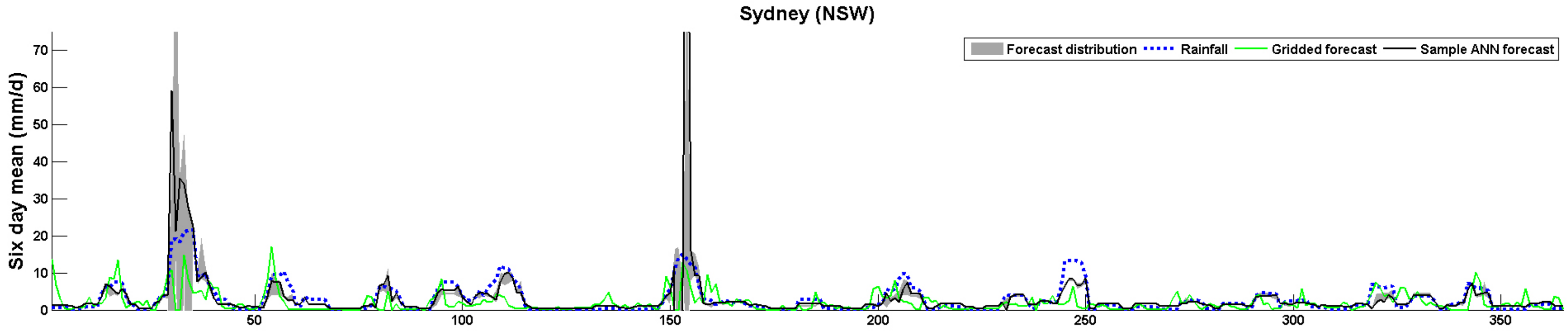

Fig. B-22 ANN rainfall estimates for 2008 in Sydney.

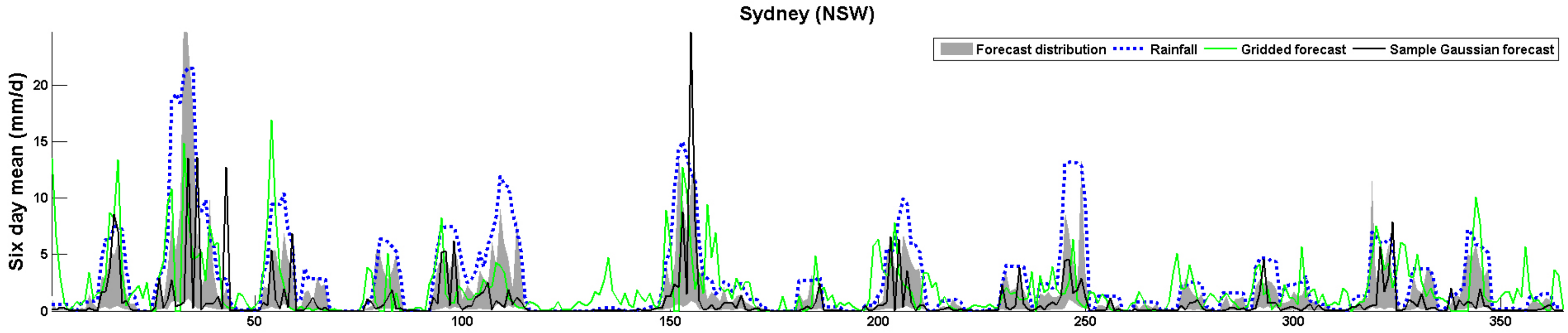

Fig. B-23 Gaussian rainfall estimates for 2008 in Sydney.

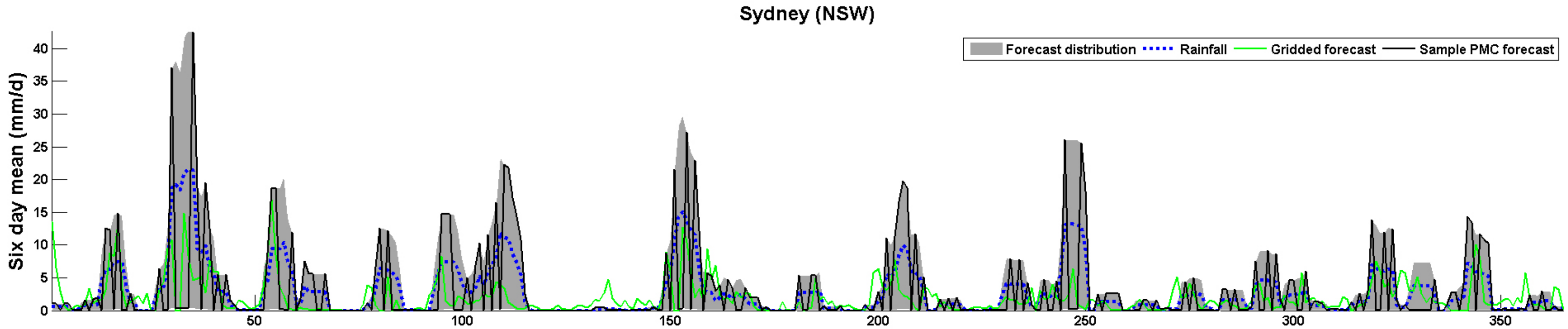

Fig. B-24 PMC rainfall estimates for 2008 in Sydney.