The relative efficiency of water supply catchments and rainwater tanks in cities subject to variable climate and the potential for climate change [*]

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SUMMARY: *This study has analysed the relative efficiencies of runoff into dams supplying Brisbane, Melbourne, Perth and Sydney, and of rainwater harvesting in those cities. It is shown that both respond differently to drought and climate change forcing, with decentralised rainwater harvesting systems in cities exhibiting a more uniform performance across these stressors. The impact of natural variations in climate is considerable, with the inland catchments that supply cities exhibiting a disproportionate decrease in yield in response to rainfall reductions, as compared to rainwater tanks in the cities. A 50% decrease in median rainfall at each location results in a 60% to 85% reduction in runoff to dams and a 15% to 30% reduction in yield from 3 kL rainwater tanks. Rainwater yields from 3 kL tanks in the cities were more resilient to the potential for climate change than runoff into dams supplying the cities. Reductions in runoff from the worst case climate change scenario ranged from 19% to 53%, while reductions in yields from rainwater tanks were 5% to 8%. Yields from rainwater tanks in cities were also more resilient to droughts than runoff into dams. This study highlights the potential for rainwater tanks in cities to supplement water supply from dams during droughts and to buffer the expected impacts of climate change.*

1 INTRODUCTION

The majority of water supplied to Australian cities has, until recently, been sourced from rainfall runoff collected from inland catchments. Australia experiences a highly variable climate that has required the construction of large dams to provide a secure water supply to cities. The future reliability of urban water supplies dependent on single centralised sources of water is uncertain due to the combined pressures of population growth, a highly variable climate and the potential for climate change.

It is now recognised that multiple sources of water from centralised and decentralised locations, in combination with a diverse range of water conservation strategies, can increase the resilience and reliability of a city's water supply (PMSEIC, 2007). Nevertheless, the water available in our cities from rainwater, stormwater and wastewater sources is not fully exploited. To illustrate this, figure 1 shows the average annual water balances from households in Brisbane, Sydney, Melbourne and Perth, and figure 2 shows the sources of urban water supply in Australia (PMSEIC, 2007; Kaspura, 2006; Coombes, 2004).

Figure 1 reveals that the combined volumes of stormwater and wastewater discharging from households (and their allotments) in each of the cities are greater than the volume of water demands at each location. Indeed the average annual volumes of stormwater discharged from households is greater than water demand in Brisbane and Sydney. Figure 2 shows that only a small proportion of

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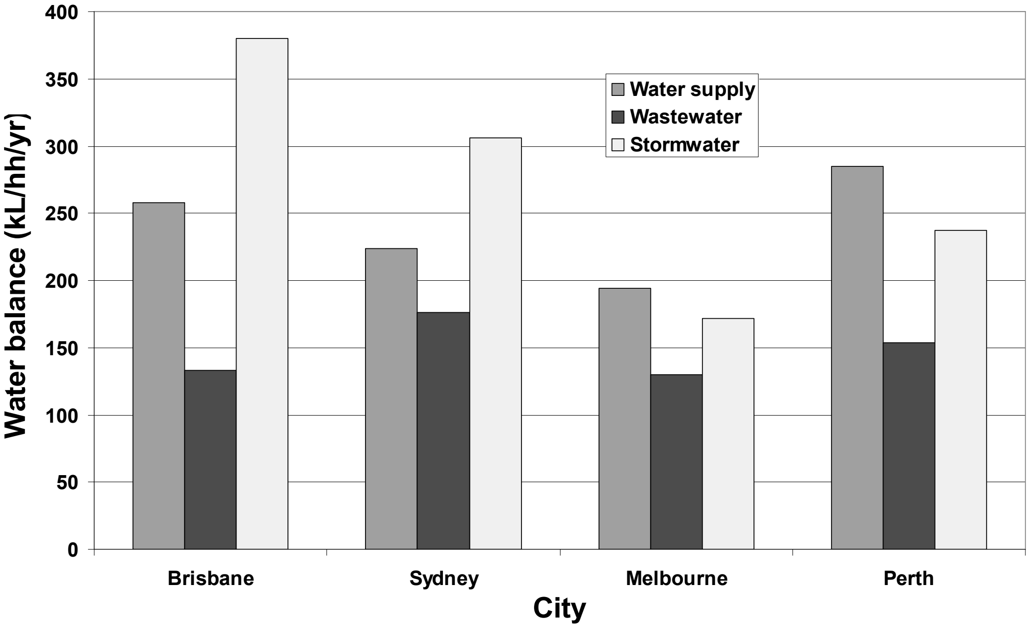

Figure 1: Average annual water balances from households in Brisbane, Sydney, Melbourne and Perth.

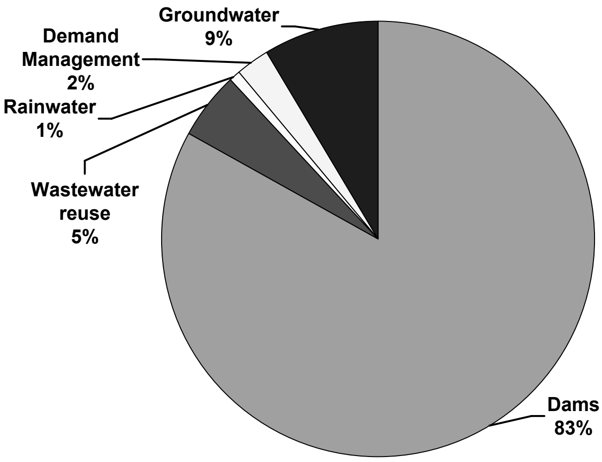

Figure 2: Sources of urban water (2004/05 water year).

urban water demand is currently met by either rainwater harvesting or wastewater reuse. As such, a considerable excess of water, on an annual average basis, is available in our cities that has not been utilised.

It was postulated by Coombes (2002) and Coombes & Kuczera (2003) that the efficiency of the water supply catchments is considerably less than roof catchments feeding rainwater tanks in urban areas. It has also been shown that in dry years (rainfall < 500 mm) the annual runoff in water supply catchments is insignificant. In these years, water losses to the soil and atmosphere balances most of the rainfall, and as a result water supplies to cities are almost totally dependent on water stored in dams from more bountiful years and from aquifers. In contrast, the roof catchment, being impervious, only experiences a small loss at the commencement of each rain event and is able to harvest the majority of rainfall, up until storage overflow. As a result, a rainwater tank can harvest beneficial volumes of water even during drought years. This result suggests that rainwater harvesting in cities can supplement the performance of dams, providing an overall improvement in the resilience of urban water supplies. The concept of relative catchment efficiency is proposed in figures 3 and 4, using the Warragamba catchment supplying Sydney as an example.

Figure 3 shows that runoff into Warragamba Dam supplying Sydney diminishes considerably at lower annual rainfall depths to a threshold of no runoff at an annual rainfall of about 500 mm. In figure 4, it is proposed that during years of limited runoff into dams a significant volume of rainwater can be harvested from roof catchments within the city. Roof catchments are expected to have a high relative efficiency for harvesting rainwater in comparison to catchments supplying dams. In addition, the impact of climate change is expected to decrease the efficiency of inland water supply catchments relative to roof catchments in a city.

This study compares the impact of historical variations in climate and predicted climate change for 2030 on runoff into dams and the yield from 3 kL rainwater tanks supplying laundry, toilet and outdoor uses in Australian capital cities of Brisbane, Melbourne, Perth and Sydney.

2 METHODS

This study utilises continuous simulation and long climate records to compare the efficiency of inland catchments supplying water to Brisbane, Sydney, Melbourne and Perth to the efficiency of rainwater tanks supplied by roof catchments in those cities.

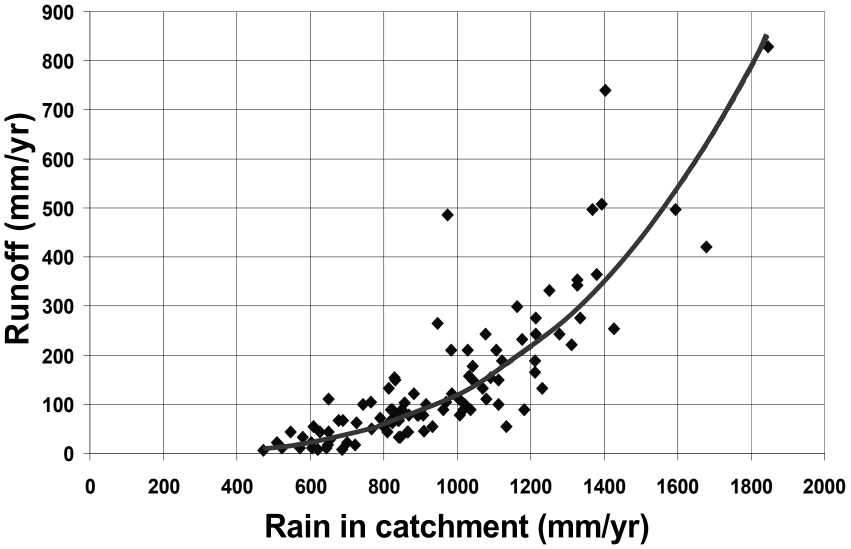

Figure 3: Efficiency of Warragamba Dam supplying Sydney.

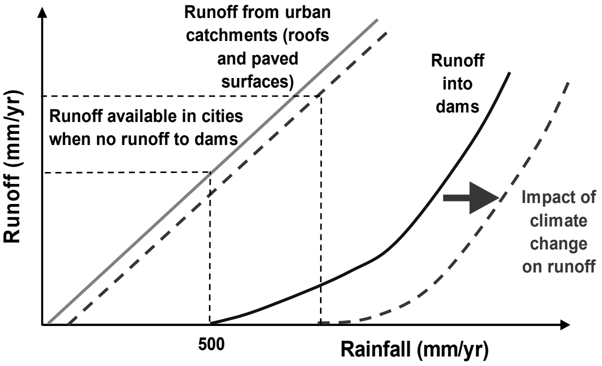

Figure 4: Conceptual relative catchment efficiency.

These catchment efficiencies are then evaluated using the expected climate change scenarios for each location.

2.1 The potential for climate change in 2030

The expected changes in temperature (table 1) and rainfall (table 2) in 2030 were sourced from Walsh et al (2002) for Queensland, Hennessy et al (2004) for New South Wales, DSE (2006) for Victoria and from IOCO (2005) for Western Australia.

2.2 Analysis of rainwater tanks

The performance of rainwater tanks is primarily dependent on local water demands and climate, and this performance is conditioned on secondary variables of roof area and size of the rainwater tank (Coombes & Barry, 2006). In order to capture these potential limits on harvesting roof runoff, the PURRS (probabilistic urban rainwater and wastewater reuse simulator) by Coombes (2006) was used to

Table 1: Expected change in average temperatures in 2030.

Location	**Increase in temperature (°C) during a given season**			
	Spring	**Summer**	**Autumn**	**Winter**
Brisbane	0.2-2	0.2-1.3	0.2-1.3	0.2-1.3
Sydney	0.2-1.6	0.2-1.6	0.2-1.6	0.2-1.8
Melbourne	0.3-1.6	0.3-2	0.2-1.6	0.2-1.4
Perth	0.5-2	0.5-2.1	0.5-2	0.5-2

Table 2: Expected change in average rainfall in 2030.

Location	**Change in rainfall (%) during a given season**			
	Spring	**Summer**	**Autumn**	**Winter**
Brisbane	–15, +5	–5, +15	–15, +15	–15, +15
Sydney	–20, +7	–7, +14	–14, +7	–7, +7
Melbourne	0, –20	–15, +10	–10, +3	–10, +3
Perth	–15, 0	–15, +5	–15, 0	–15, 0

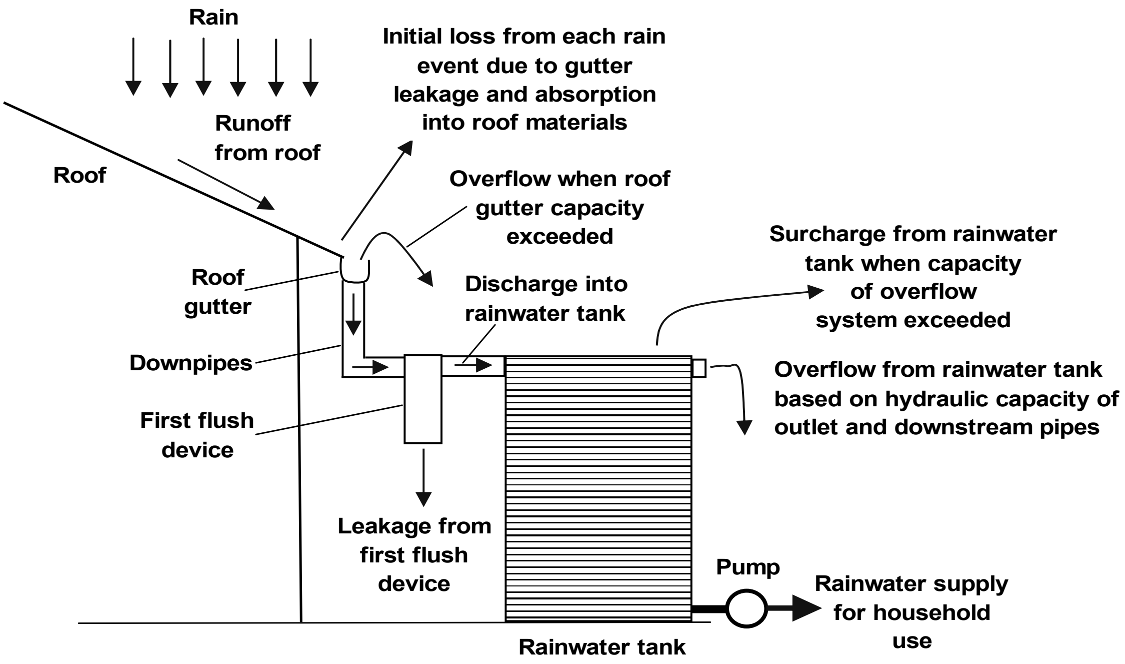

Figure 5: Schematic of the roof runoff to rainwater tank processes in PURRS.

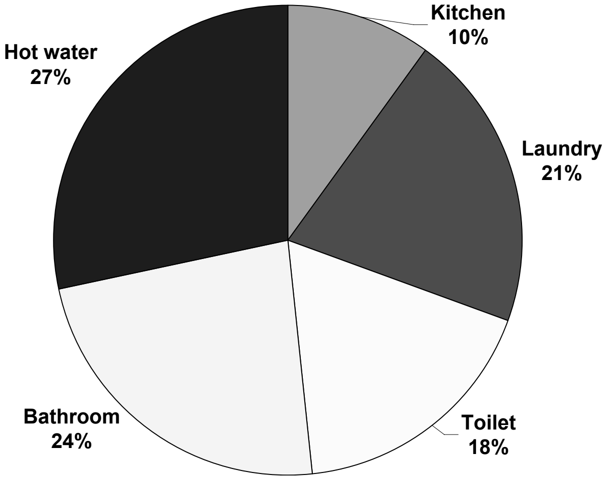

Figure 6: Distribution of household water use categories.

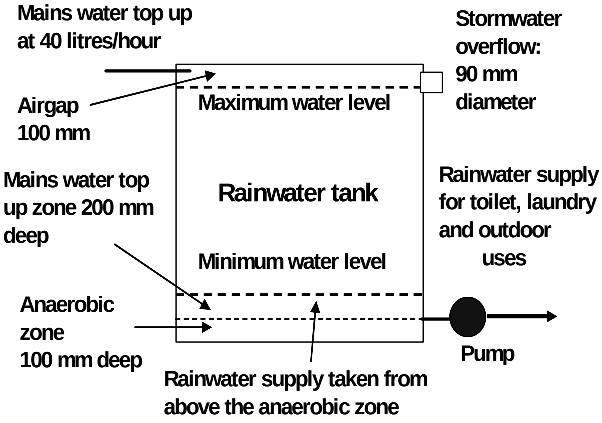

Figure 7: Configuration of rainwater tanks.

continuously simulate (at 6 minute time steps) the performance of 3 kL rainwater tanks capturing runoff from 150 m^2 roofs to supply laundry, toilet and outdoor uses in each city.

Rainfall inputs to the model were from pluviograph rainfall data. Rainfall falling on roof areas discharges to a first flush device with a capacity of 20 L and if the capacity of the roof gutter system is exceeded, rainfall also overflows from the roof gutter system to impervious areas. Rainwater is then routed through the first flush device to a rainwater tank (figure 5).

Water is drawn from the rainwater tank for household laundry, toilet and outdoor uses in accordance with the distribution of end uses shown in figure 6 and, if the water level in the rainwater tank is below a set minimum level, the tank is topped up with mains water at a nominated rate (figure 7). Mains water is used to supply all household uses not sourced from the rainwater tank and to supplement the rainwater tank supply.

A full description of the PURRS model can be sourced from Coombes (2006). An important advance in the simulation of roof runoff process as shown in figure 5 has been included in the PURRS model. Roof runoff processes used in the model do not include arbitrary initial and continuing losses. These processes may be adequate for stormwater runoff from rural or urban non-roof catchments, but are not relevant to rainwater harvesting from roofs. Roof systems are relatively impervious and are not subject to significant evapotransporation or infiltration losses. More accurately, these systems are subject to losses that are based on leakage from roof gutter systems and overflows from roof gutter systems when the capacity of gutters and down pipes is exceeded. The arbitrary use of inappropriate initial and continuing losses in analysis of domestic rainwater harvesting creates considerable errors.

Monitoring studies by the Coombes (2002) has revealed that initial gutter losses range from 0 to 0.8 mm of roof runoff with the average initial gutter losses being about 0.5 mm. This study has employed an initial gutter loss of 0.5 mm.

2.2.1 *Climate data used in PURRS*

Pluviograph (6 minute) rainfall and daily temperature records were sourced from the Australian Bureau of Meterology used in the PURRS model at each location as shown in table 3.

2.2.2 *Water demand data used in PURRS*

Household water demand was derived using data from the Australian Bureau of Statistics, State of the Environment Reports and Water Services Association Australia (WSAA) facts as previously reported by Coombes & Barry (2006). Average water demands for three-person households at each location from the PURRS simulations are shown in table 4.

The data in table 4 was used as inputs to the probabilistic behavioural water demand algorithms embedded in the PURRS model. It is important to note that the water demand algorithms in the PURRS model allow for climate generated daily and diurnal variation of water demands that use information from table 4 as conditioning variables. The PURRS demand algorithms allow for daily and diurnal variation of water use while maintaining the expected long-term monthly volumes of water use.

2.3 Analysis of water supply catchments

The SIMHYD model (eWater, 2006) was used to continuously simulate (at a daily time step) the performance of the inland water supply catchments for each location using the rainfall and potential evaporation data shown in table 5.

These catchment models were calibrated as best as possible to publicly available data sourced from The Sydney Catchment Authority, The Queensland Department of Natural Resources and Water, The Victorian Department of Sustainability and Environment, and the Western Australian Water Corporation. Given the limitations of data available for this study, SIMHYD was calibrated to annual runoff. The calibration for the water supply catchments supplying Brisbane, Melbourne, Perth and Sydney are shown in figures 8, 9, 10 and 11.

Table 3: Data from the Australian Bureau of Meteorology used in the PURRS model.

Location	Station number	Start date	End date	Average rainfall (mm/a)	Years in record
Brisbane Regional Office	40214	1/02/1911	31/12/1993	1093	83
Melbourne Regional Office	86071	1/01/1925	31/12/2000	646	76
Perth Metro + Perth Airport	9225	1/01/1946	31/12/2000	811	55
Sydney Observatory Hill	66062	1/01/1913	31/12/1998	1203	86

Table 4: Average water demands derived for three-person households at each location.

Location	Total demand (kL/a)	Total demand (kL/d)	Outdoor demand (kL/d)
Brisbane	217	0.594	0.257
Melbourne	203	0.557	0.136
Perth	362	0.992	0.366
Sydney	303	0.831	0.160

Table 5: Data from the Australian Bureau of Meteorology used in the SYMHYD model.

Location	Rainfall record	Evaporation record	Start date	End date
Brisbane	Toogoolawah	Somerset Dam	1/01/1909	31/12/2007
Sydney	Goulburn	Goulburn TAFE	1/01/1900	31/12/2007
Melbourne	Jamieson	Reefton	1/01/1900	31/12/2007
Perth	Serpentine	Dwellingup	1/01/1942	31/12/2006

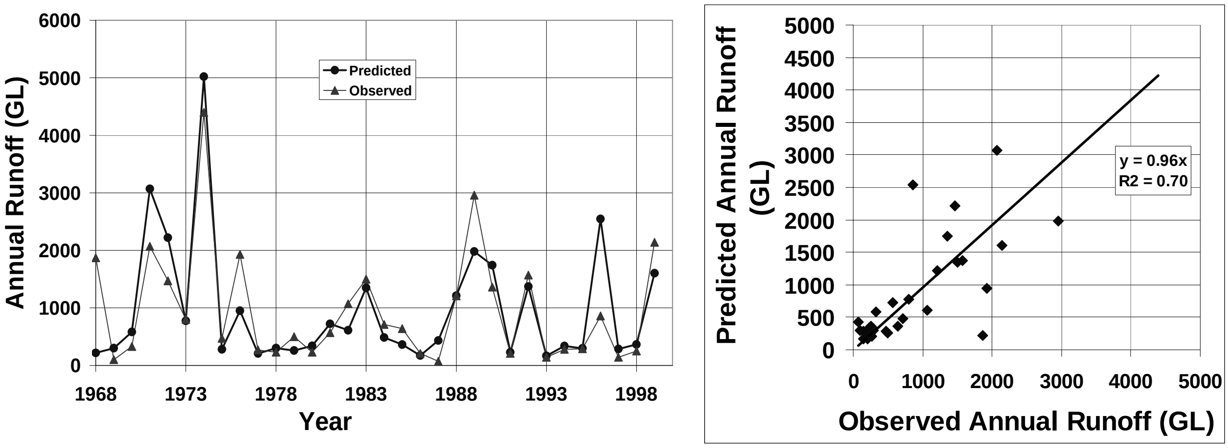

Figure 8: Calibration results for runoff into Wivenoe Dam supplying Brisbane.

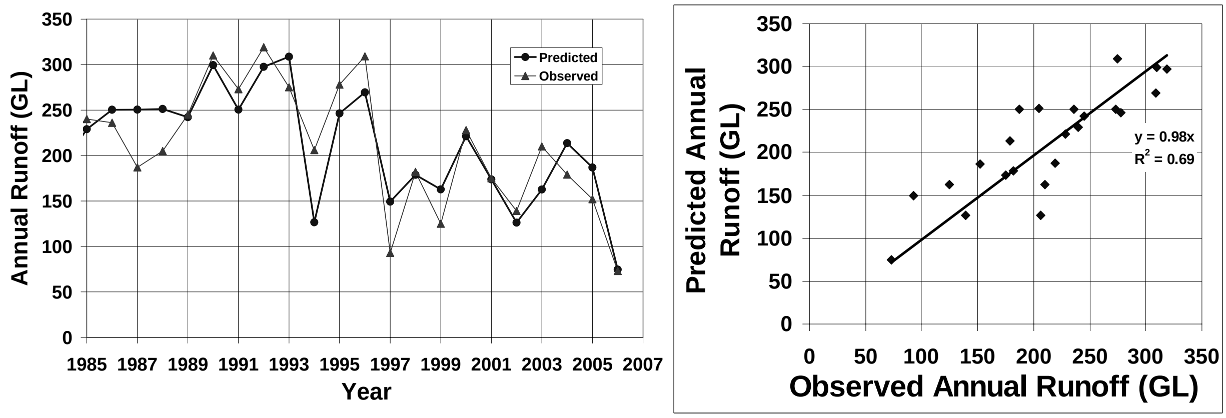

Figure 9: Calibration results for runoff into Thomson Dam supplying Melbourne.

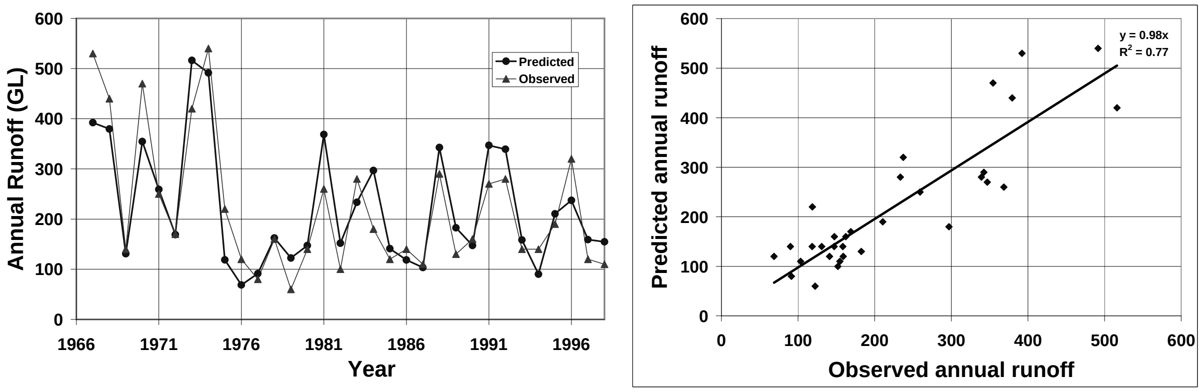

Figure 10: Calibration results for runoff into the South East Dams supplying Perth.

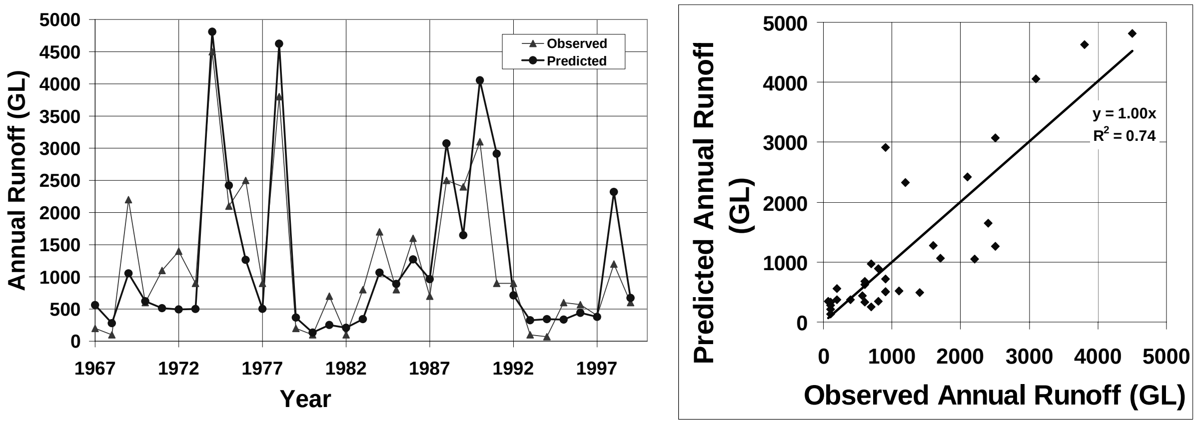

Figure 11: Calibration results for runoff into the Warragamba Dam supplying Sydney.

The impact of climate change in 2030 was simulated after applying the expected changes in temperature and rainfall to the historical climate records. Four climate change scenarios were simulated that accounted for combinations of high rainfall, low rainfall, high temperature and low temperature. The predicted temperature changes were translated to changes in PET in the SYMHYD models by assuming that changes in temperature were proportional to changes in PET.

3 RESULTS

The response of water supply catchments and 3 kL rainwater tanks supplied by roof catchments were simulated using historical and climate change scenarios. It was observed that responses of the water supply catchments were most impacted by the low rainfall and high temperature scenario, indicating that drying of the water supply catchments also has a significant impact on yield. In contrast, the responses of the rainwater tanks were most impacted by the low rainfall and low temperature scenarios due to the dependence of urban water demand on temperature. Higher temperatures will generate higher water demands, which will increase yields from rainwater tanks. In contrast, the responses of the two systems to variation in annual rainfall depth were significant and variable.

Long-term sequences of rainfall and runoff into dams at each location were examined to understand influence of wet and dry climate cycles on runoff, which may better describe runoff processes than speculation about rapid climate change. Whiting et al (2007) described this phenomenon as hydrological persistence. The yields from water supply catchments and rainwater tanks were compared for each location using the non-dimensional numbers annual rainfall divided by median rainfall, and annual yields divided by median yield. Yields from rainwater tanks during low inflows to dams at each location as defined by the lowest 10 percentile of inflow were then analysed to understand the effectiveness of rainwater tanks during droughts.

3.1 Patterns of hydrological persistence in water supply catchments

The observed annual rainfall and simulated sequence of runoff into Wivenoe Dam supplying Brisbane are shown in figure 12.

Figure 12 shows that the Wivenoe Dam catchment has been generally subjected to wet and dry cycles, with higher rainfall during the period 1927 to 1976, which has generated higher runoff. This relatively wetter period cumulates in significantly higher runoff during the years 1971 to 1976 with the highest runoff in the period experienced during 1974.

The catchment has also experienced periods of lower rainfall that extend from 1909 to 1926 and 1977 to 2006, with the lowest rainfall occurring during 1977, 1992 and 1993. Importantly, the catchment has experienced four extended periods of significantly lower runoff during 1909 to 1926, 1977 to 1980, 1993 to 1995 and 2000 to 2006. The most severe period of low runoff occurs during 1909 to 1926. Clearly, the current drought may not be the worst in the record and the industry practice of comparing the current annual runoff to the highest runoff in 1974 will provide a misleading view of rapid change in runoff patterns. It is possible that rainfall and runoff patterns at Wivenoe Dam have returned to a dryer state evident earlier in the century.

The observed annual rainfall and simulated sequence of runoff into Thomson Dam supplying Melbourne are shown in figure 13.

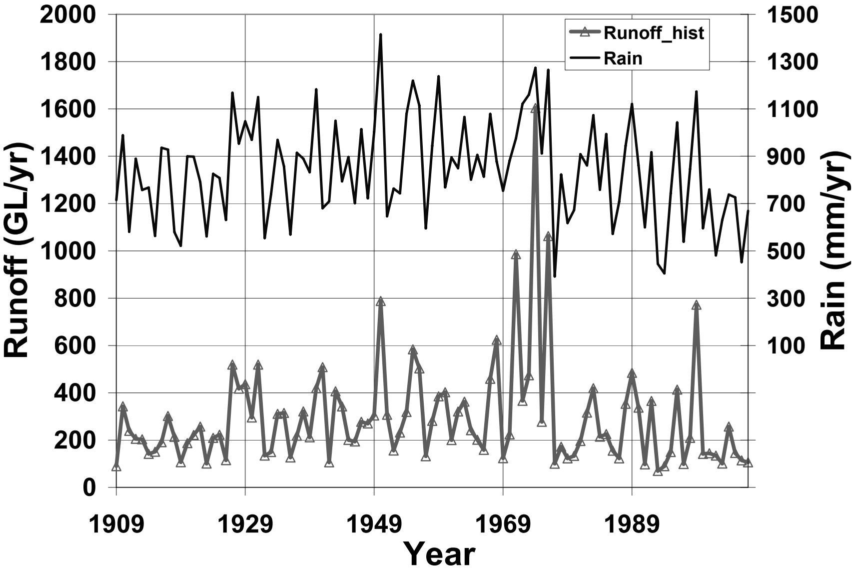

Figure 12: Rainfall and runoff sequences at Wivenoe Dam supplying Brisbane.

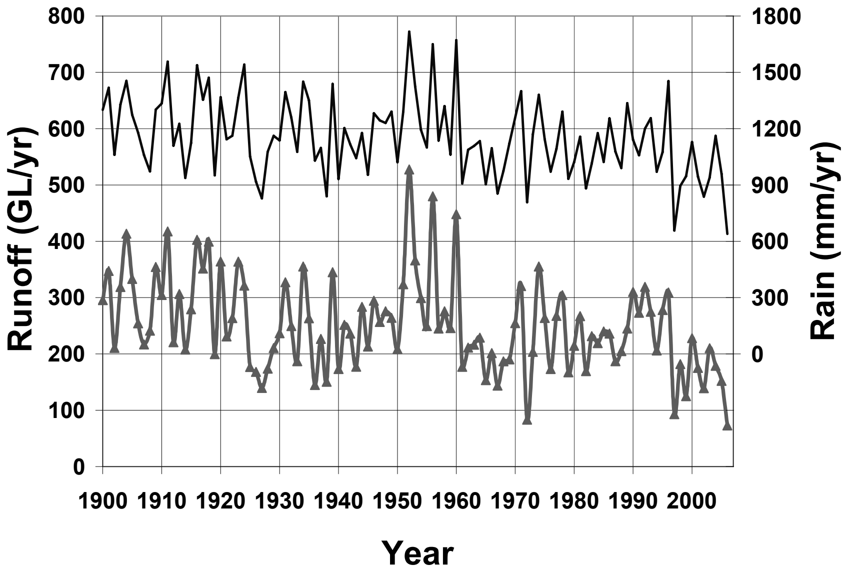

Figure 13: Rainfall and runoff sequences at Thomson Dam supplying Melbourne.

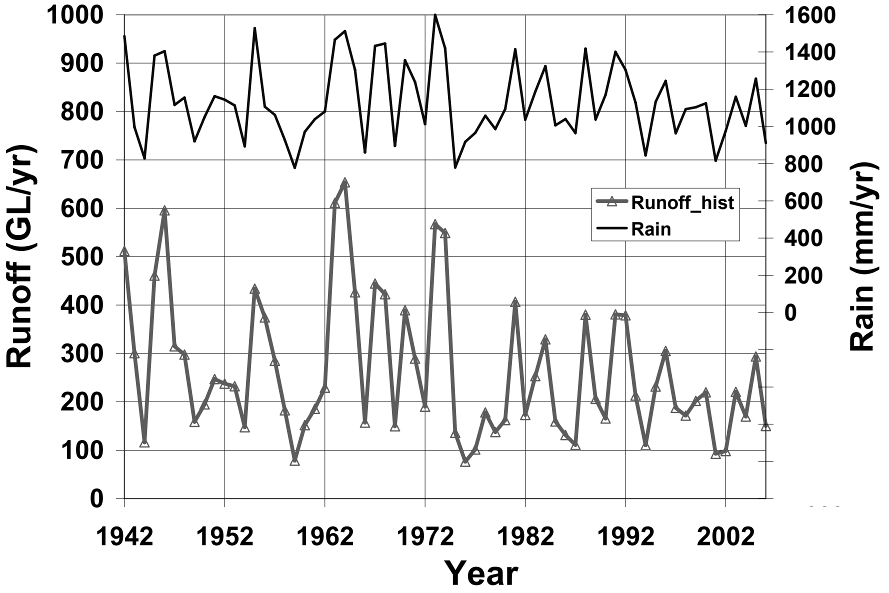

Figure 14: Rainfall and runoff sequences at the South East Dams supplying Perth.

Figure 13 shows that the catchment supplying Thomson Dam is also subject to cycles of lower and higher rainfall. The highest runoff occurred during the period 1951 to 1960, with periods of extended low runoff experienced during 1925 to 1930, 1961 to 1969 and 1997 to 2006. The current drought has generated the longest period of low runoff in the record. It is also evident that Thomson catchment may have been subject to a trend to declining runoff during the period.

The observed annual rainfall and simulated sequence of runoff into the South East Dams supplying Perth are shown in figure 14.

Figure 14 reveals that the catchments supplying the South East Dams were also subject to cycles of wetter and dryer climate. The highest rainfall and runoff was experienced during the period 1963 to 1974. Lower rainfall and runoff occurred during the periods 1948 to 1954, 1958 to 1962 and 1975 to 2006, with the lowest runoff in the record experienced during 1959. The current drought may not include the lowest runoff in the record and the industry practice of comparing the current annual runoff to the highest runoff in 1974 will provide a misleading view of rapid change in runoff patterns.

The observed annual rainfall and simulated sequence of runoff into Warragamba Dam supplying Sydney are shown in figure 15.

Figure 15 shows that the Warragamba catchment also experiences cycles of wetter and dryer periods with a trend to increased rainfall and runoff during the period 1947 to 1989. The catchment was subject to low runoff during the period 1900 to 1910, 1935 to 1941, 1978 to 1982 and the current drought extending from 1990 to 2007. The current drought may not be the worst in the record and the industry practice of

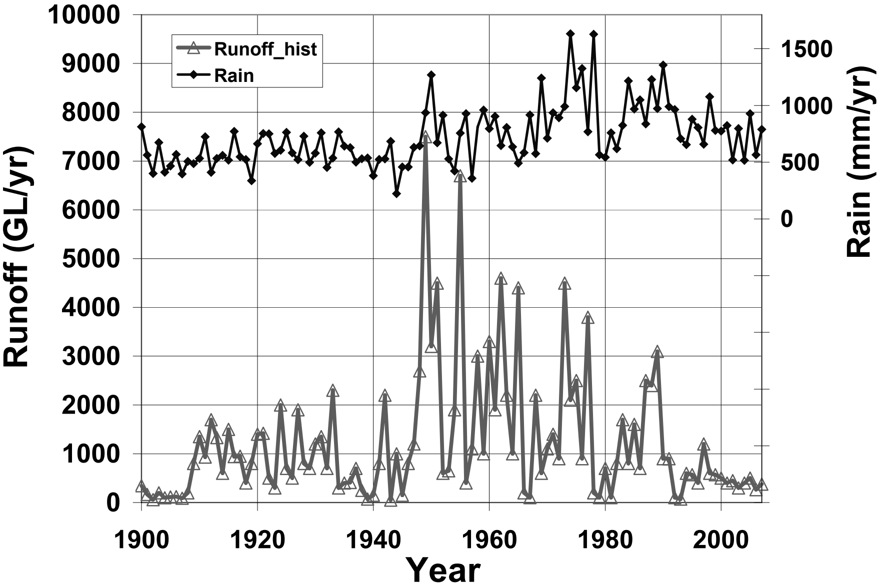

Figure 15: Rainfall and runoff sequences at Warragamba Dam supplying Sydney.

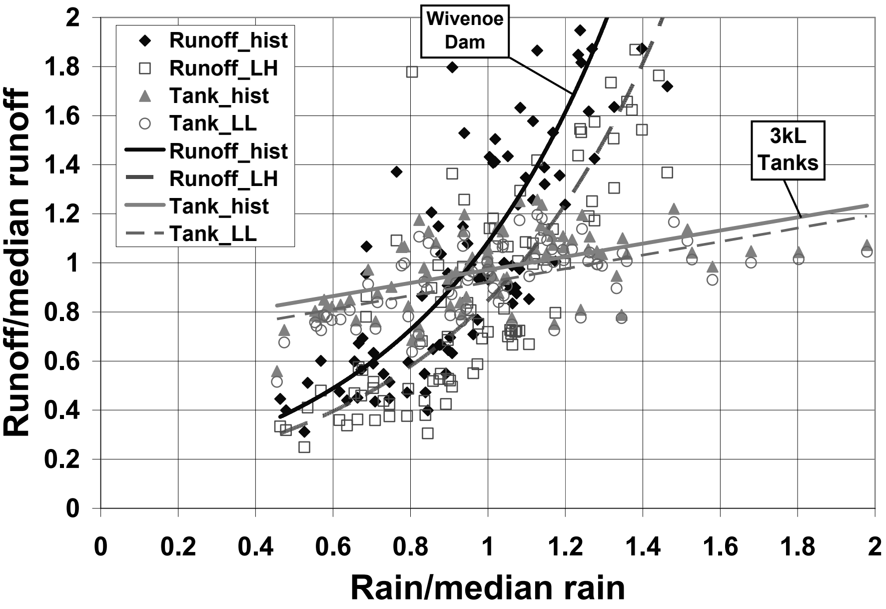

Figure 16: Comparative response of catchments and rainwater tanks to climate variation and change in Brisbane.

comparing the current annual runoff to the runoff in the wetter period during 1947 to 1989 will provide a misleading view of rapid change in runoff patterns. It is possible that rainfall and runoff patterns at Warragamba Dam have returned to a dryer state evident earlier in the century.

3.2 Catchment and rainwater tank response to climate variation and change

The variation in rainfall and runoff into Wivenoe Dam supplying Brisbane and yields from 3 kL rainwater tanks in Brisbane is presented in figure 16.

Figure 16 shows that runoff into Wivenoe Dam is highly dependent on natural variation in rainfall. Median annual rainfall and runoff at Wivenoe Dam was 846 mm and 224 GL, respectively. The variation in rainfall is highlighted by ratios of annual rainfall to the long-term median rainfall that varies from 0.46 to 1.67, with the corresponding ratios of annual runoff to long-term runoff varying from 0.31 to 7.17. Note that some high runoff results are not shown in figure 16 to facilitate a comparative diagram.

In contrast, yields from 3 kL rainwater tanks in Brisbane display less dependence on variation in rainfall than runoff into Wivenoe Dam supplying Brisbane. Median annual rainfall and yield from 3 kL rainwater tanks in Brisbane was 1068 mm and 67 kL, respectively. The ratios of annual rainfall to the long-term median rainfall in Brisbane varies from 0.5 to 2.0, with the corresponding ratios of tank yield to long-term median tank yield varying from 0.6 to 1.3.

Median annual runoff into Wivenoe Dam from the worst case scenario for climate change in 2030 was 181 GL, which represents a 19% reduction in runoff. While median annual yields from rainwater tanks in Brisbane from the worst case scenario for climate change in 2030 were 63 kL, which represents a 5% reduction in yield.

The relative efficiency of traditional water supply catchments and rainwater tanks supplying Brisbane is highlighted by the response to a 50% decrease in median rainfall of a 60% reduction in runoff into Wivenoe Dam and a 15% reduction in yield from a 3 kL tank.

The variation in rainfall and runoff into Thomson Dam supplying Melbourne and yield from 3 kL rainwater tanks in Melbourne is presented in figure 17.

Figure 17 reveals that yields from 3 kL rainwater tanks in Melbourne are less dependent on the natural variation in rainfall than runoff into Thomson Dam supplying Melbourne. Median annual rainfall and runoff at Thomson Dam was 1137 mm and 241 GL, respectively. The ratios of annual rainfall to the long-term median rainfall varies from 0.56 to 1.51, and the corresponding ratios of annual runoff into Thomson Dam to long-term runoff varies from 0.3 to 2.19. Note that some high runoff results are not shown in figure 17 to facilitate a comparative diagram.

Median annual rainfall and yield from 3 kL rainwater tanks in Melbourne was 638 mm and 62 kL, respectively. The ratios of annual rainfall to the long-term median rainfall in Melbourne varies from 0.53 to 1.34, with the corresponding ratios of tank yield to long-term tank yield varies from 0.68 to 1.34.

Median annual runoff into Thomson Dam from the worst case scenario for climate change in 2030 was 174 GL, which represents a 28% reduction in runoff. In contrast, median annual yields from rainwater tanks in Brisbane were 58 kL, which represents an 8% reduction in yield.

The relative efficiency of traditional water supply catchments and rainwater tanks supplying Melbourne is highlighted by the response to a 50% decrease in median rainfall of a 85% reduction in runoff and a 30% reduction in yield from a 3 kL tank.

The variation in rainfall and runoff into South East Dams supplying Perth and yield from 3 kL rainwater tanks in Perth is presented in figure 18.

Figure 18 reveals that yields from 3 kL rainwater tanks in Perth are less dependent on climate variation than runoff into the South East Dams supplying Perth. Median annual rainfall and runoff to the South East Dams was 1103 mm and 220 GL, respectively. The ratios of annual rainfall to the long-term median rainfall varies from 0.7 to 1.45, with the corresponding ratios of annual runoff to long-term runoff varying from 0.35 to 2.98. Note that some high runoff results are not shown in figure 18 to facilitate a comparative diagram.

Median annual rainfall and yield from 3 kL rainwater tanks in Perth was 817 mm and 64 kL, respectively. The ratios of annual rainfall to the long-term median rainfall in Perth varies from 0.6 to 1.34, with the corresponding ratios of tank yield to long-term tank yield varies from 0.66 to 1.23.

The relative impact of expected climate change is highlighted by the median annual runoff into the South East Dams from the worst case scenario for climate change in 2030 of 103 GL, which represents a 53% reduction in runoff. In contrast, median annual

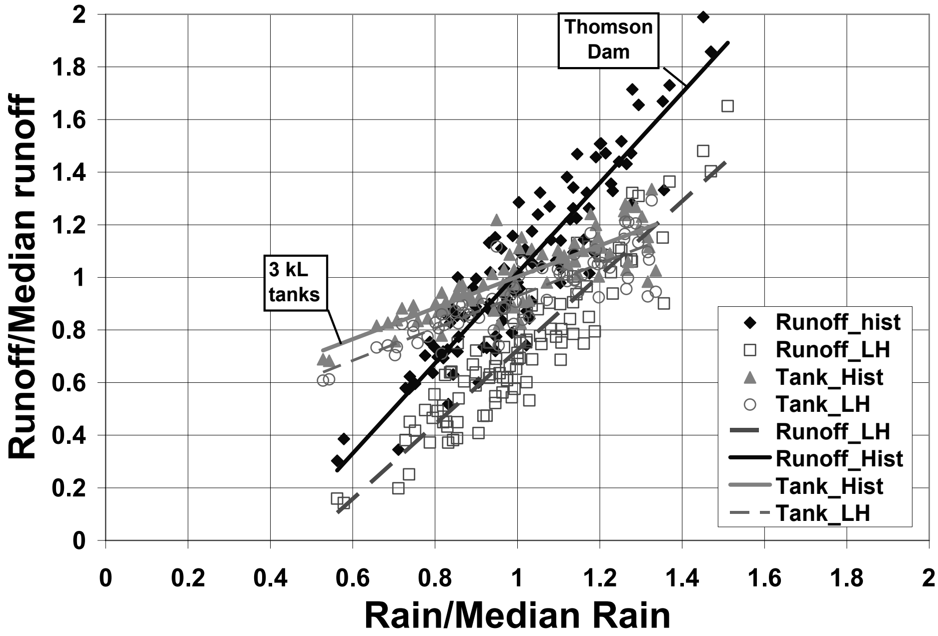

Figure 17: Comparative response of catchments and rainwater tanks to climate variation and change in Melbourne.

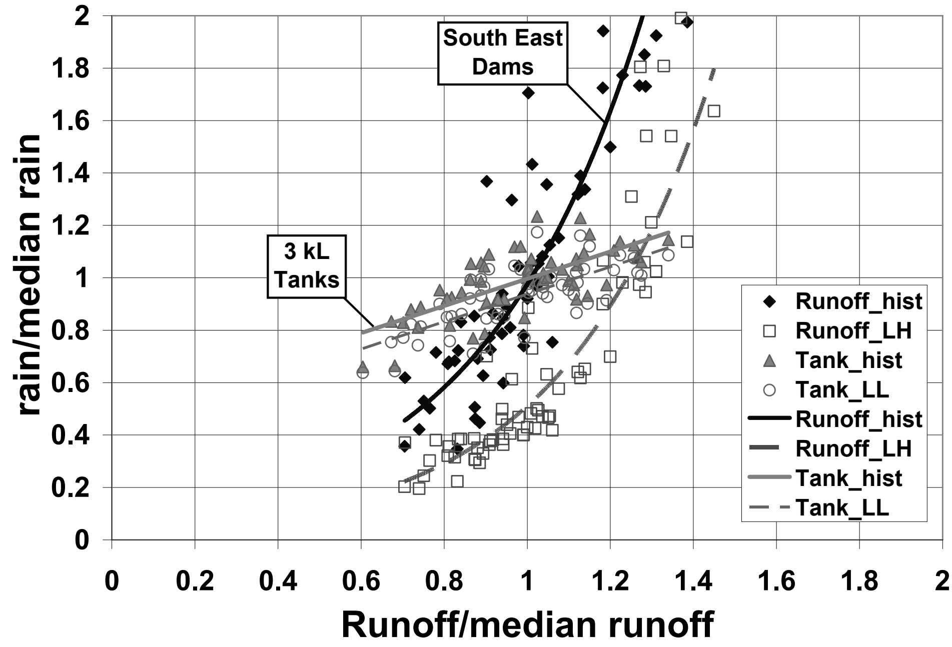

Figure 18: Comparative response of catchments and rainwater tanks to climate variation and change in Perth.

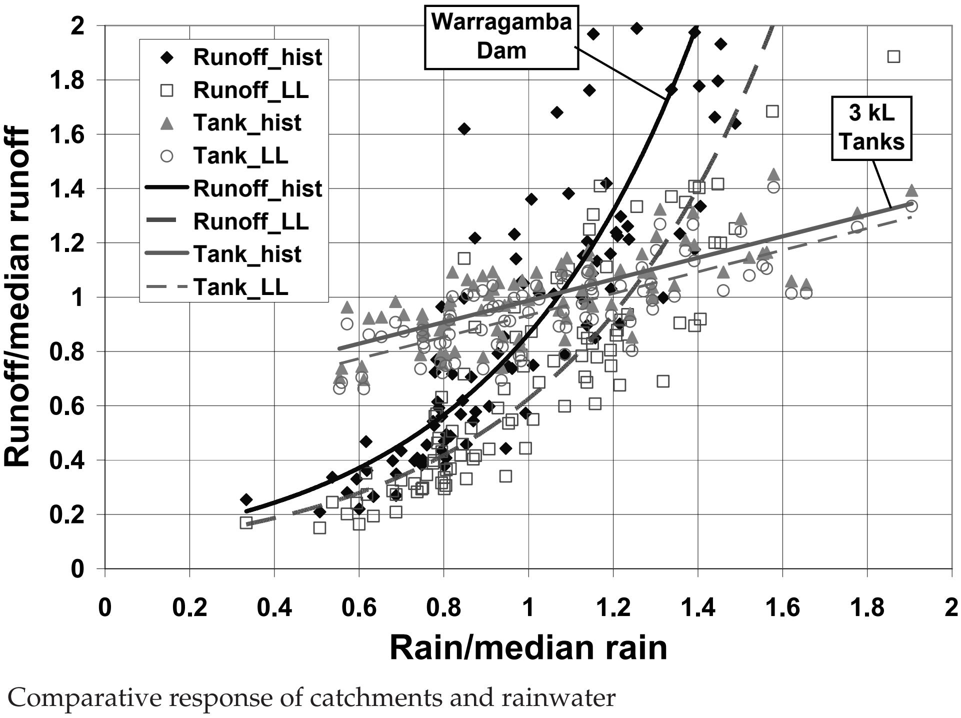

Figure 19: Comparative response of catchments and rainwater tanks to climate variation and change in Sydney.

yields from rainwater tanks in Perth from the worst case scenario for climate change in 2030 were 60 kL, which represents a 6% reduction in yield.

The relative efficiency of inland water supply catchments and rainwater tanks supplying Perth is highlighted by the response to a 50% decrease in median rainfall of a 73% reduction in runoff and a 26% reduction in yield from a 3 kL tank.

The variation in rainfall, runoff into Warragamba Dam supplying Sydney and yield from 3 kL rainwater tanks in Sydney is presented in figure 19.

Figure 19 reveals that yields from 3 kL rainwater tanks in Sydney are less dependent on variation in rainfall than runoff into the Warragamba Dam supplying Sydney. Median annual rainfall and runoff to the Warragamba Dam was 667 mm and 266 GL, respectively. The ratios of annual rainfall to the long-term median rainfall varies from 0.33 to 2.45, and the corresponding ratios of annual runoff to long-term runoff varies from 0.21 to 17.13. Note that some high runoff results are not shown in figure 19 to facilitate a comparative diagram.

Median annual rainfall and yield from 3 kL rainwater tanks in Sydney was 1141 mm and 72 kL, respectively. The ratios of annual rainfall to the long-term median rainfall in Sydney varies from 0.55 to 1.9, with the corresponding ratios of tank yield to long-term tank yield varies from 0.7 to 1.45.

The relative impacts of the potential for climate change is demonstrated by median annual runoff into the Warragamba Dam from the worst case scenario for climate change in 2030 of 189 GL, which represents a 29% reduction in runoff. Median annual yields from rainwater tanks in Sydney from the worst case scenario for climate change in 2030 were 69 kL, which represents a 5% reduction in yield.

The relative efficiency of inland water supply catchments and rainwater tanks supplying Sydney is highlighted by the response to a 50% decrease in median rainfall of a 70% reduction in runoff and a 20% reduction in yield from a 3 kL tank.

3.3 Yield from rainwater tanks during low inflows to dams

It is commonly assumed that rainwater tanks will not provide mains water savings during droughts. To evaluate the efficiency of rainwater tanks and runoff into dams during droughts, median annual yields from tanks and from water supply catchments were evaluated for all years in the simulation that correspond with the lowest 10% of inflows from the catchments supplying dams. This was considered to be a drought scenario. The impact of the potential for climate change on the drought scenario was also evaluated. Results for yields from rainwater tanks in Brisbane and runoff into Wivenoe Dam during droughts are compared to historical results in table 6.

Results for yields from rainwater tanks in Melbourne and runoff into Thomson Dam during droughts are compared to historical results in table 7.

Results for yields from rainwater tanks in Perth and runoff into South East Dams during droughts are compared to historical results in table 8.

Results for yields from rainwater tanks in Sydney and runoff into Warragamba Dam during droughts are compared to historical results in table 9.

Tables 6 to 9 show that the majority of reductions in runoff and rainwater yields was due to the impacts of droughts, with smaller additional reductions in yield attributed to climate change. Yields from rainwater tanks in cities were more resilient to droughts and climate change than runoff into dams supplying cities.

Table 6: The impact of droughts and climate change on runoff into Wivenoe Dam and yields from rainwater tanks in Brisbane.

Criteria	Drought yield	Reduction (%)	Climate change yield	Reduction (%)
Runoff to dam	103 GL	54	81 GL	64
Rainwater yield	54 kL	20	51 kL	24

Table 7: The impact of droughts and climate change on runoff into Thomson Dam and yields from rainwater tanks in Melbourne.

Criteria	Drought yield	Reduction (%)	Climate change yield	Reduction (%)
Runoff to dam	142 GL	41	96 GL	60
Rainwater yield	51 kL	17	47 kL	25

Table 8: The impact of droughts and climate change on runoff into the South East Dams and yields from rainwater tanks in Perth.

Criteria	Drought yield	Reduction (%)	Climate change yield	Reduction (%)
Runoff to dams	92 GL	58	48 GL	78
Rainwater yield	60 kL	7	54 kL	15

Table 9: The impact of droughts and climate change on runoff into Warragamba Dam and yields from rainwater tanks in Sydney.

Criteria	Drought yield	Reduction (%)	Climate change yield	Reduction (%)
Runoff to dams	82 GL	69	56 GL	79
Rainwater yield	72 kL	0	68 kL	5

4 DISCUSSION

The analysis presented in this paper forms part of a larger study to examine the impacts of rainwater tanks on water cycle management throughout Australia that is subject to ongoing contextual analysis. This paper provides some insight into the relative efficiencies of traditional (centralised) catchment systems supplying cities and distributed (decentralised) rainwater harvesting facilities within cities.

There is considerable divergence in the response of inland catchments supplying dams and rainwater tank in cities to a variable climate and the potential for climate change. Centralised water supply systems dependent on dams are more sensitive to changes in rainfall (particularly in reduced runoff during reduced rainfall periods) than rainwater tanks in cities. Importantly, this analysis supports the argument for inclusion of rainwater harvesting from roof catchments in cities within the overall suite of strategies to improve water security in our capital cities. It is not suggested that large scale centralised infrastructure is not needed (it is), but that we could benefit significantly from diversifying the water sources we draw on to meet demand, particularly during droughts and other periods of stress, including climate change.

4.1 Evidence of hydrologic persistence

Each of the water supply catchments were subject to highly variable rainfall and runoff that indicated cycles of wetter and dryer periods. This variation was characterised by higher rainfall and runoff during the mid 1900s, and lower rainfall and runoff was also observed at the beginning and end of the 1900s.

There is widespread speculation that the current drought is the worst on record and that water supply catchments are subject to rapid declines in rainfall and runoff. However, the current drought may not have produced the most severe reductions in runoff from catchments supplying Brisbane, Perth and Sydney. Runoff from those catchments may have returned to lower levels that were evident earlier in the 1900s. In contrast, there appears to be a gradual decline in rainfall and runoff in the Thomson Catchment supplying Melbourne.

It is clear from figures 12 to 15 that the common practice of comparing runoff from the wettest period in the 1900s to current levels of runoff will produce a misleading perception of rapid changes in the hydrology in each catchment. In addition, the different rainfall patterns and hydrological responses at each of the catchments highlight the need for detailed spatial understanding of rainfall and hydrological processes. The use of average assumptions about rainfall and runoff may not lead to a robust understanding of the processes in each catchment.

4.2 Impacts of a variable climate

The study demonstrates that each of the catchments is subject to highly variable rainfall. Figures 16 to 19 demonstrate that inland water supply catchments and rainwater tanks do indeed behave differently in response to historical variations in rainfall. The most notable trend is that inland water supply catchments supplying cities exhibit a disproportionate decrease in yield in response to rainfall reductions, as compared to rainwater tanks in the cities. A 50% decrease in median rainfall at each location results in a 60% to 85% reduction in runoff to dams and a 15% to 30 % reduction in yield from 3 kL rainwater tanks.

This may be, at least in part, due to the pervious nature of catchments that generally require significant re-wetting following reduced rainfall in order to generate appreciable runoff. In contrast, rainwater tanks have highly impervious roof catchments and are, therefore, largely immune to the hysteresis exhibited by catchments in runoff generation.

At the higher rainfall extreme, water supply catchments tend to generate proportionally greater runoff than rainwater tanks. The maximum ratios of annual runoff to long-term annual median runoff ranges from 17.13 to 2.19 for inland catchments supplying dams, and the maximum ratio of annual yields from rainwater tanks to long-term annual median yields ranges from 1.3 to 1.45. It is noteworthy that the catchments supplying Brisbane and Sydney are subject to the highest ratio of runoff to median runoff.

These differences are, at least partially, attributable to the loss of water in rainwater tank systems due to overflow events, which occur much more frequently than those associated with dams on inland catchments. In addition, these results highlight the potential of inland catchments, with large areas, to harvest considerable volumes of runoff during high rainfall years.

4.3 Impacts of the potential for climate change in 2030

Rainwater yields from 3 kL tanks in the cities were more resilient to the potential for climate change than runoff into dams supplying the cities. Reductions in runoff from the worst case climate change scenario ranged from 19% to 53%, while reductions in yields from rainwater tanks were 5% to 8%. Runoff into the South East dams supplying Perth was most impacted by the potential for climate change.

The climate change scenario with low rainfall and high temperature produced the lowest runoff in most of the inland catchments. It is expected that higher temperatures increased evapotranspiration from the catchments. Lower rainfall on dryer catchments would then generate greater infiltration losses to soils and reduce the frequency of runoff events. There was no significant difference between the low and high temperature scenario for the catchment supplying Sydney. The reason for this result is unknown.

In contrast, the climate change scenario with low rainfall and low temperature generated the lowest yields from rainwater tanks. The rainwater yields from tanks are primarily dependent on water demands and the water use algorithms in the PURRS model rely on climate variables, including maximum daily temperature. The high temperature scenario results in higher water demands, which increased the yields from the rainwater tanks. As such, the climate change scenario with lower temperatures created the lowest rainwater yields.

The potential for increased water demands due to the expected higher temperatures in the various climate change scenarios should be considered in the planning for future water security.

4.4 Impacts of drought

This study has arbitrarily defined a drought as a period where runoff into dams is equal to less than the 10 percentile of runoff at each location. These defined periods of drought produce very high reductions in runoff into dams ranging from 41% to 69% that correspond to lower reductions in yields from rainwater tanks ranging from 0% to 20%.

Yields from rainwater tanks in cities were more resilient the impacts of drought than runoff into dams. This result highlights the potential for rainwater tanks in cities to supplement water supply from dams during droughts. It is important that rainwater tanks in cities also supply water during wetter periods, thereby reducing water demands from dams during more plentiful years, allowing greater carryover storage of water in dams for use in droughts. This improves the overall reliability of the water supply system.

4.5 A comment on assumptions and limitations of this study

This study has relied on SIMHYD models calibrated to annual sequences of runoff in water supply catchments that may not have adequately captured all of the climatic drivers of hydrological process in each catchment. The analysis of rainwater tanks in this study was also limited to a single rainwater harvesting scenario at one location in each city. Nevertheless, it is the view of the authors that a strong comparative analysis has been presented in this paper that has significant implications for water resource management in Australia.

Further studies should consider a range of rainwater tank sizes, associated demands, end uses and locations in each city. For example, this study has utilised rainfall at Melbourne Regional Office, one of the lowest average annual rainfall depths in Melbourne, to analyse the relative performance of rainwater tanks. Melbourne, like all cities examined in this study, is subject to considerable spatial variation in annual rainfall depths. Current research by the authors suggests that impacts of variation and climate change on rainwater yields are strongly dependent on spatial location within cities.

5 CONCLUSIONS

This paper has presented an analysis of the relative efficiency of the response of water supply catchments supplying cities and rainwater harvesting systems in cities to a variable climate and the potential for climate change. The results presented in this paper indicate that roof catchment systems supplying rainwater tanks were significantly more resilient to natural variations in climate and expected climate change than water supply catchments supplying dams.

Decentralised rainwater harvesting from roof catchments in cities has the potential to supplement centralised water supply strategies to create an overall more resilient urban water supply. This result highlights the importance of implementing a diverse range of water sources and conservation strategies for urban water management.

In the context of calls for rainfall independent water supply options, this study highlights the importance of considering the relative efficiency of various water supply options in the context of geographical location. The efficiency of translation of rainfall into runoff is highly dependent on strategy and location. Urban water strategies should also consider the synergistic benefits of combined strategies (such as water supply from rainwater harvesting and from dams), which include improved reliability of urban water supplies and the potential to buffer the impacts of expected climate change.

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