Urban Rainwater Harvesting – Analysis of a Decentralized Approach for Meeting Water Demand in Urban Cities. An Opportunity for the US?

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ABSTRACT

This study uses the Probabilistic Urban Rainfall and wastewater Reuse Simulator (PURRS) to investigate variability in mains water savings and stormwater runoff when a decentralized approach is used to meet water demand in urban cities. Two Integrated Water Cycle Management (IWCM) options were investigated, Demand Management (DM) and Rainwater Tanks (RWT). Continuous simulation was performed with different water demands and roof areas on 6,458 ft^2 allotments in Sydney, Brisbane and Melbourne, Australia. The extents of benefits are dependent upon climate regime and water demand however the results indicated that there is plenty of water available at the allotment scale and that rainwater harvesting offers significant mains water savings and stormwater reductions for urban areas. This decentralized approach to meeting water demand is being implemented in Australia and the opportunity exists for the same savings to be realized in the United States.

INTRODUCTION

The analysis of regional water strategies carried out by State governments, water authorities and their consultants in Australia report that insufficient water resources are available to meet increasing water demands that are a consequence of a growing population. These studies usually recommend large centralized engineering solutions for an alternative water source including installation of desalination plants and large scale wastewater recycling schemes that sometimes require citizens to drink treated wastewater that will be stored in water supply reservoirs. It should be recognized that drinking water (potable) demand is only about 1% of total water use in a city.

Studies such as this typically dismiss decentralized solutions including rainwater harvesting without critical analysis. The results seems to be a relic of the current vested interests in centralized management of water supplies, dividend returns to government from the sale of water, and consultants that are dependent on the current centralized governance structure. However, as shown in the following Figures 1a, 1b and 1c, the volume of stormwater runoff from a 6,458 ft^2 house lot with 3,229 ft^2 urban roof and 807 ft^2 of other impervious surfaces, is very often greater than the volume of mains water supplied to residential dwelling (4 people).

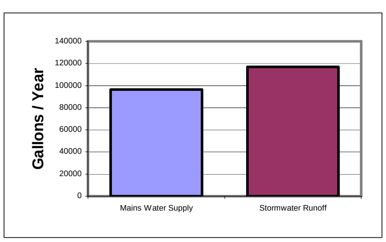

Figure 1a – Average Household

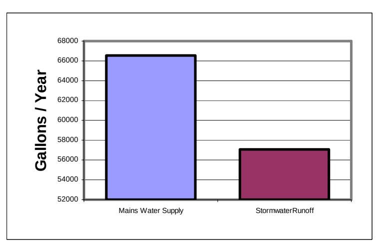

Figure 1b – Average Household

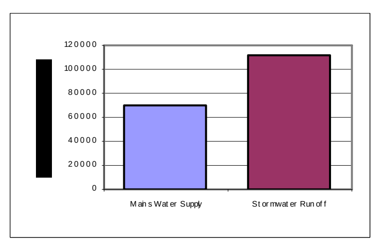

Figure 1c – Average Household

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Water Balance in Sydney **Water Balance in Melbourne** **Water Balance in Brisbane**

As such there is often a considerable excess of water available at the allotment and the magnitude of this excess of available water is dependent on location. Given that an excess of water is available at the decentralized scale (at the allotment), one must ask why many regional water supply strategies find that insufficient water is available and recommend large centralized solutions. This is further exacerbated when consideration is given to the efficiency of a residential roof rainwater catchment area compared to a water supply catchment as shown in Figure 2.

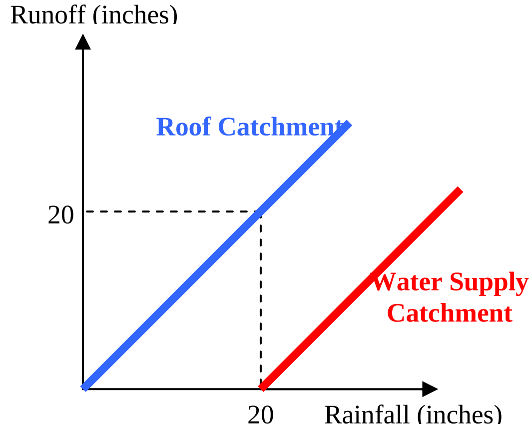

Figure 1 – Harvest efficiencies of natural and roofed catchments.

Simplified plots of annual runoff against annual rainfall for water supply catchments typically display a threshold effect. Once annual rainfall falls below about 20 inches, annual runoff in water supply catchments is insignificant. In such years evapotranspiration and infiltration accounts for virtually all of the rainfall and the water supply system is almost totally dependent on water stored from more bountiful years. In contrast a roofed catchment, being impervious, only experiences a small loss at the commencement of each rain event. As a result, a rainwater tank can harvest significant volumes of water even during drought years. Roofs are more efficient than water supply catchments for harvesting rainwater. This result also indicates that roof catchments will be more reliable than water supply catchments in climate change scenarios.

Fortunately, rainwater harvesting systems are becoming a new paradigm in sustainable urban water cycle management. The harvesting of rainwater provides an additional water supply and as a consequence reduces the stormwater runoff. In addition, significant reductions in operating costs and greenhouse gas emissions of regional water supplies have been observed (Coombes 2006). This paper has been written largely based upon a paper by Lucas. A.L., Coombes, P.J. and Geary, P.M., *Continuous Simulation of Rainwater Tank, Wastewater Storage and Stormwater runoff: The Influence of Climatic Regimes, Water Demand and Diurnal Flow Patterns*, presented at Water 2006 in New Zealand.

Recent studies in Australia (Coombes et al, 2002; Coombes and Kuczera, 2003; Coombes, 2005a; Coombes 2005b) and overseas (Vaes and Berlamont, 2001; Qiang, 2003; Villarreal and Dixon, 2005) have highlighted the significant cost and environmental benefits of decentralizing and integrating water supply systems, particularly with respect to traditional designs. Traditionally designed supply and stormwater systems have environmental and cost limitations with respect to expanding urban areas and populations, available water sources and end-use water quality issues not previously envisaged by water authorities. Over the past decade, approaches to improve urban water cycle management have included water-saving devices inside the home, the use of rainwater tanks, reuse of treated wastewater and water sensitive urban design (WSUD) principles to manage stormwater runoff.

When several IWCM (Integrated Water Cycle Managemet) options are implemented in unison at an allotment scale, various levels of mains water savings and stormwater runoff reductions can be obtained. This study uses the PURRS (Probabilistic Urban Rainwater and wastewater Reuse Simulator) (Coombes, 2002) model to continuously simulate demand management (water saving devices) and the performance of rainwater harvesting to explore the reductions in mains water supply and stormwater runoff that are available at an allotment scale.

Too often rainwater tanks in urban areas are used only to provide water for outdoor uses such as garden watering. As a result, the tank is only utilized during the growing season. If, however, the tank is used for internal non-potable applications toilet flushing, laundry and hot water, which represent a significant fraction (about 85%) of indoor usage, the tank is constantly being drawn down. This has two key benefits. First, for small storm events much of the potential runoff is captured by the tank – that is why use of the rainwater tanks produces considerable reduction in stormwater runoff for small Average Recurrence Interval (ARI) storm events. Second, because toilet flushing, laundry water and hot water are sourced from the rainwater tank, the base load on the mains water system is reduced. As a result, centralized water storage reservoirs will fill more rapidly during periods of good streamflow. In centralized systems with over-year storage capacity, the reduction in base demand provides a buffer against the effects of droughts and growth in water demand due to population growth.

Importantly Coombes et al. [2000; 2000a; 2002a] and Spinks et al. [2003; 2003a] found that the quality of water supply from rainwater tanks was acceptable for hot water, toilet, and outdoor uses. Spinks et al. [2003] confirmed that E. Coli and selected pathogens are rapidly eliminated from water heated to temperatures above 131°F by the processes of heat shock and pasteurisation. Note that OSHA recommends domestic hot water heaters be maintained at 140°F and water delivered at the faucet at a minim of 122°F. In Australia, ASNZ2500.2.4 requires that hot water systems be set to heat water to 60°C (140°F) to eliminate Legionella Spp. from mains water.

METHOD

The PURRS (Probabilistic Urban Rainwater and wastewater Reuse Simulator) model [Coombes and Kuczera, 2001] was used in combination with the DRIP event based synthetic rainfall model [Heneker et al,. 2001] to evaluate the effectiveness of rainwater tanks in each city.

The PURRS model was used to analyze the performance of 1,320 gallon (5 kL) rainwater tanks used to supply domestic hot water, toilet, laundry and outdoor uses. Continuous simulation of the performance of rainwater tanks was conducted at time steps of 6 minutes over a period of 100 years using synthetic pluviograph rainfall records generated by DRIP. Hot water, laundry and toilet use was estimated to be 85% of indoor water demand. When a water level in a rainwater tank falls below a minimum depth of 8 inches (200mm), the tank is topped up with mains water to a minimum level at a rate of 10.6 gallons (40L) per hour (Figure 3).

In the model, rainfall was directed from roofs via first flush devices with a volume of 5.3 gallons (20L) to the rainwater tanks. An initial loss of 1/32 inch (0.5mm) was assumed from the roofs. The rainwater tanks are topped up by mains water at a rate of 10.6 gallons (40L) per hour when the water levels were drawn below a minimum water level located 8 inches (200mm) from the base of the tank (Figure 3). Full details of the PURRS model can be found in Coombes (2001).

The performance of rainwater tanks connected to dwellings with roof areas of 1,615 ft^2 (150 m^2), 2,153 ft^2 (200 m^2) and 3,229 ft^2 (300 m^2) with 1 to 5 occupants was analyzed in this study. The average annual reduction in mains water use and the average retention storage volume available prior to storm events is used to assess the performance of the IWCM options.

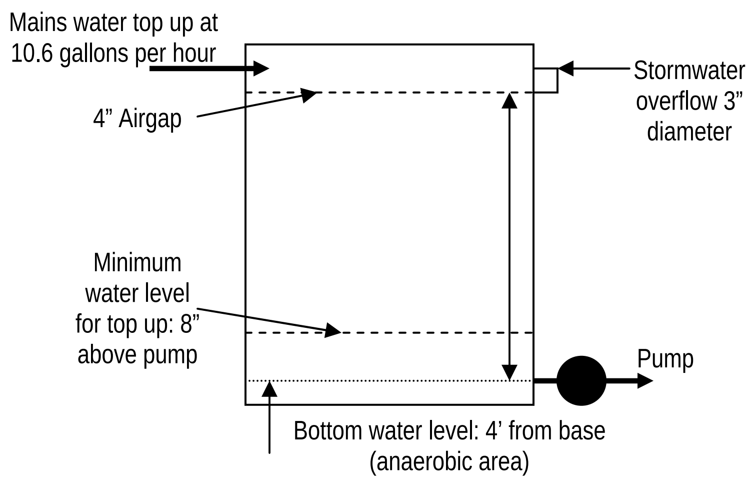

Figure 3 – Rainwater Tank Configuration as used in PURRS

Two IWCM options were evaluated in this study and are shown in Table 1.

STRATEGY	ABBREVIATION	OCCUPATION	ROOF AREA (ft^2)
Demand Management only	DM only	1, 2, 3, 4, 5 people	1615, 2153, 3229
Demand Management + Rainwater Tank	DM + RWT	1, 2, 3, 4, 5 people	1615, 2153, 3229

Table 1: IWCM strategies evaluated in this study

Hypothetical allotment configurations used in this study are shown in Figure 4, that include houses with 1,615, 2,153 and 3,229 ft^2 roof areas on 6,458 ft^2 allotments, and include 807 ft^2 of other impervious area (driveway, paths and so on).

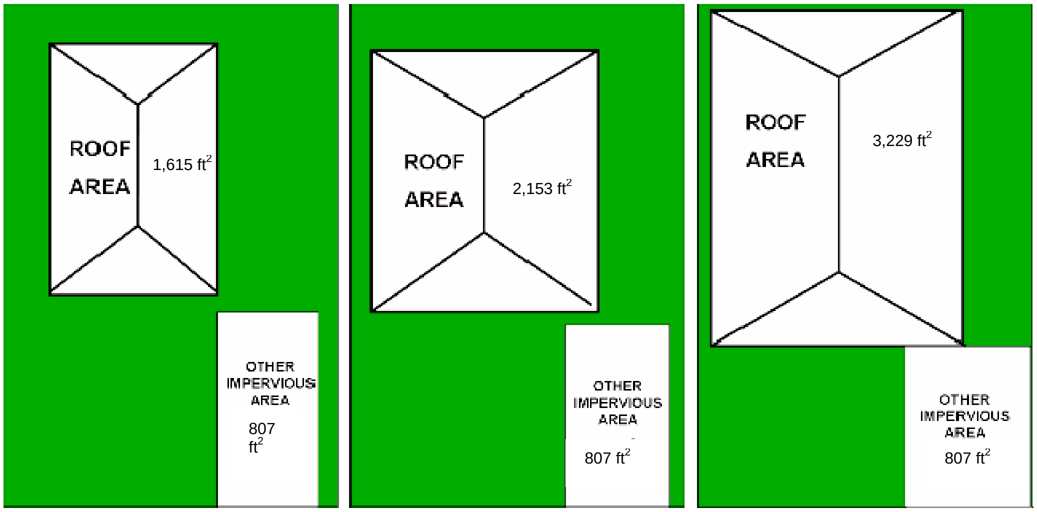

Figure 4: Allotment areas and impervious areas used for each scenario

CLIMATE DATA

The IWCM strategies were continuously simulated in, Sydney, Melbourne and Brisbane using climate data, including pluviograph rainfall (6 minute intervals); sourced from the Australian Bureau of Meteorology (BOM). The annual average rainfall depths, rainfall distribution, length of rainfall record and water demand distribution for each location are shown in Table 2. This data will be referred to during discussion to highlight the effect that rainfall depth, distribution of water demand and rainfall have on MWS (Mains Water Supply) and SWR (Stormwater Reductions).

LOCATION	ANNUAL AVERAGE RAINFALL (inches)	RELATIVE RAINFALL DEPTH/ DISTRIBUTION	WATER DEMAND DISTRIBUTION	YEARS OF SIMULATION
Sydney Observatory Hill	47.2	High - Uniform	Summer	86
Melbourne Regional Office	25.4	Low - Uniform	Summer	76
Brisbane Airport	43.0	High - Summer	Summer	83

Table 2: Annual average rainfall, relative rainfall depth, and rainfall and water demand distribution with the number of years used in the continuous simulation

Water demand

All simulations used water demand data that was derived for 1, 2, 3, 4 and 5 person households. Table 3 summarizes the indoor, outdoor and total water demands used during simulation of each IWCM option. Values for indoor and total demand are with respect to the number of people (left to right, 1 to 5 people) and outdoor use for a 6,458 ft^2 allotment was considered constant regardless of the number of people.

LOCATION	No of PEOPLE	INDOOR (gallons/day)	OUTDOOR (gallons/yr)	TOTAL DEMAND (gallons/yr)
Sydney	1,2,3,4,5	60.8, 113.6, 169.1, 221.9, 280.0	15,533	37618, 56903, 77138, 96423, 117636

Melbourne	1,2,3,4,5	37.0, 74.0, 108.3, 145.3, 179.6	13,182	26998, 40498, 53046, 66545, 79067
Brisbane	1,2,3,4,5	26.4, 50.2, 84.5, 124.2, 153.2	24859	34712, 43403, 55925, 70402, 80995

Table 3: Indoor, outdoor and total water demands used in this study

The demand management (DM) option includes the use of water efficient toilets, shower roses and washing machines. In the demand management and rainwater tank (DM + RWT) option, includes rainwater harvesting supplying outdoor, toilet, laundry and hot water uses.

RESULTS

Results are presented as mains water savings and stormwater runoff in gallons/yr for each location. The rainwater tank was assumed to have capacity of 1,320 gallons. Mains water savings expressed as a percentage of total water demand are also shown in a separate Table for each location.

SYDNEY

Annual average mains water savings significantly increased with increasing occupancy for the DM + RWT option. DM only provided minimal mains water savings. Mains water savings increased with larger roof areas for our DM + RWT strategy.

Benefit	Roof Area	DM	DM + RWT
Mains Water Savings	1,615 ft^2	3,434 to 15,850 gallons	2,219 to 43,324 gallons
Mains Water Saving	3,229 ft^2	3,434 to 15,850 gallons	25,889 to 53,099 gallons

Table 4 – Average Annual Mains Water Savings for 1 to 5 person Households, Sydney

Stormwater runoff (SWR) volumes generally decreased with increasing occupancy for the DM + RWT scenario, and remained relatively constant across 1 to 5 person households for the DM only scenario.

Benefit	Roof Area	DM	DM + RWT
Stormwater runoff	1,615 ft^2	75,289 gallons	56,269 to 47,815 gallons
Stormwater runoff	3,229 ft^2	117,028 gallons	94,574 to 80,044 gallons

Table 5 – Average Annual Stormwater Runoff for 1 to 5 person Households, Sydney

Table 6 shows mains water savings as a percentage of total allotment water demand for Sydney. The DM only scenario reduced mains water use by 8.7% to 12.9% for 1 to 5 person households respectively. Significant reductions in mains water use were achieved using the rainwater harvesting strategy. For 1 to 5 person households with 1,615 ft^2 roof areas the DM + RWT scenario reduced mains water use by 58.6% to 35.3% and by 68.1% to 43.3% for 3,229 ft^2 roof areas. Annual average mains water savings were observed to decrease with increasing occupancy and increased mains water savings were observed with respect to increasing roof area for a given occupancy.

		No of People				
SYDNEY	**Roof Area (ft^2)**	**1**	**2**	**3**	**4**	**5**
DM only	1615, 2153, 3229	8.7%	10.9%	11.9%	12.5%	12.9%
DM + RWT	1,615	58.6%	48.7%	42.6%	38.4%	35.3%
DM + RWT	2,153	64.8%	54.5%	47.8%	42.0%	38.7%
DM + RWT	3,229	68.1%	58.2%	51.6%	46.9%	43.3%

Table 6: Percentage Main Water Savings in Sydney

BRISBANE

Mains water savings significantly improved with increasing occupancy for our DM + RWT option. Small mains water savings were provided for the DM only scenario. Annual average mains water savings increased with larger roof areas for the DM + RWT strategy but were independent of roof area for the DM only scenario.

Benefit	Roof Area	DM	DM + RWT
Mains Water Savings	1,615 ft^2	1585 to 7132 gallons	19813 to 31965 gallons
Mains Water Saving	3,229 ft^2	1585 to 7132 gallons	22983 to 38833 gallons

Table 7 – Average Annual Mains Water Savings for 1 to 5 person Households, Brisbane

Annual average stormwater runoff (SWR) volumes generally decreased with increasing occupancy for the DM + RWT scenario, and remained relatively constant across 1 to 5 person households for the DM only scenario.

Benefit	Roof Area	DM	DM + RWT
Stormwater runoff	1,615 ft^2	75,553 gallons	57590 to 52306 gallons
Stormwater runoff	3,229 ft^2	111,216 gallons	89819 to 81100 gallons

Table 8 – Average Annual Stormwater Runoff for 1 to 5 person Households, Brisbane

Table 9 shows mains water savings in Brisbane as a percentage of total allotment water demand. The DM only scenario reduced mains water use by 4.7% to 10.4% for 1 to 5 person households respectively. Significant reductions in mains water use were achieved using the rainwater harvesting strategy. For 1 to 5 person households with 1,615 ft^2 roof areas the DM + RWT scenario reduced mains water use by 61.5% to 42 %, and by 64.1% to 46.5% for 3,229 ft^2 roof areas. Mains water savings were observed to decrease with increasing occupancy and increased mains water savings were observed with respect to increasing roof area for a given occupancy.

		No of People				
BRISBANE	**Roof Area (ft^2)**	**1**	**2**	**3**	**4**	**5**
DM only	1615, 2153, 3229	4.7%	6.8%	8.5%	9.8%	10.4%
DM + RWT	1,615	54.7%	49.6%	44.9%	40.6%	38.3%
DM + RWT	2,153	61.5%	56.0%	50.7%	44.4%	42.0%
DM + RWT	3,229	64.1%	59.0%	53.9%	49.1%	46.5%

Table 9: Percentage Main Water Savings in Brisbane

MELBOURNE

Annual Average mains water savings were seen to increase with greater occupancy for the DM + RWT option. The DM only scenario provided small mains water savings. Mains water savings increased with larger roof areas for DM + RWT strategy and was independent of roof area in the DM only scenario.

Benefit	Roof Area	DM	DM + RWT
Mains Water Savings	1,615 ft^2	2113 to 10039 gallons	17964 to 30644 gallons
Mains Water Saving	3,229 ft^2	2113 to 10039 gallons	20605 to 41739 gallons

Table 10 – Average Annual Mains Water Savings for 1 to 5 person Households, Melbourne

Annual average stormwater runoff (SWR) volumes generally decreased with increasing occupancy for the DM + RWT scenario, and remained relatively constant across 1 to 5 person households for the DM only scenario.

Benefit	Roof Area	DM	DM + RWT
Stormwater runoff	1,615 ft^2	32229 gallons	30644 to 16643 gallons
Stormwater runoff	3,229 ft^2	57061 gallons	41739 to 20605 gallons

Table 11 – Average Annual Stormwater Runoff for 1 to 5 person Households, Melbourne

Table 12 shows mains water savings as a percentage of total allotment water demand in Melbourne. The DM only scenarios reduced mains water use by 7.8% 12.4% for 1 to 5 person households respectively. For 1 to 5 person households with 1,615 ft^2 roof areas the DM + RWT scenario reduced mains water use by 65.1% to 37.9% and by 75% to 51.7% for 3,229 ft^2 roof areas. Reductions in annual average mains water savings were observed to decrease with increasing occupancy and increased reductions in mains water savings were observed with respect to increasing roof area for a given occupancy.

		No of People				
MELBOURNE	**Roof Area (ft^2)**	**1**	**2**	**3**	**4**	**5**
DM only	1615, 2153, 3229	7.8%	10.1%	11.3%	12.0%	12.4%
DM + RWT	1,615	65.1%	54.8%	47.3%	41.9%	37.9%
DM + RWT	2,153	71.8%	62.7%	55.2%	48.3%	44.7%
DM + RWT	3,229	75%	67.5%	61.4%	56.1%	51.7%

Table 12: Reductions in mains water demand in Melbourne

DISCUSSION

The results show that significant mains water savings can be made by implementing decentralized water cycle management strategies. Further to this, there are significant stormwater savings for decentralized water cycle management strategies that embrace rainwater harvesting. Also, results indicate that in the cities reviewed there is not a water shortage as publicized by the water industry, only gross inadequacies in the centralized approaches used by the water industry. The DM only scenarios provided relatively small mains water savings and no reductions in stormwater runoff. Alternatively the DM + RWT scenario significantly decreased mains water use and decreased stormwater runoff.

The IWCM strategies at the locations evaluated, namely Sydney, Brisbane and Melbourne resulted in a range of mains water savings and stormwater runoff reductions. These locations also have a diversity of climatic regimes and water demands that influenced the relative benefits to be gained from a given IWCM option. For example annual rainfall and water demand patterns are somewhat similar in Sydney, Brisbane and to a lesser extent Melbourne. At these locations, rainfall maxima generally coincide with increased demands and rainfall minima coincide with low water demands. However, the mains water savings observed cannot be explained solely by the climatic regime. As such we must look to the influence of water demand on yields from rainwater tanks to further explain the differences in mains water savings between Sydney, Brisbane and Melbourne. For example, Melbourne and Brisbane have relatively lower water demands than Sydney, although Brisbane has significantly greater rainfall than Melbourne or Sydney. As such, rainwater tank options in Brisbane would be expected to provide greater mains water savings than in Melbourne – but this was not always the case. Inspection of water demand at lower occupancies showed that Melbourne experiences larger indoor water demands than Brisbane, meaning that yields from tanks in Melbourne was greater than rainwater yields in Brisbane for lower household occupancies. As a result, rainwater tank options provided greater relative mains water savings in Melbourne than Brisbane for lower occupancy; however the difference between mains water savings between Melbourne and Brisbane diminished with increasing occupancy and roof area.

In contrast, Sydney has a moderate rainfall annual depth but a relatively large water demand compared to Melbourne and Brisbane. Therefore, since Sydney experiences significantly higher water demands then it follows that rainwater tank drawdown would also be at a maximum. Even though there is relatively less rainfall in Sydney than Brisbane, the scenario of moderate rainfall with good correlation between rainfall distribution and water demand distribution, and high water demand, means rainwater tanks provide comparable mains water savings to Brisbane.

For all locations, significant reductions were observed in stormwater runoff for the DM + RWT scenario. The implications for reducing stormwater runoff are economic and environmental. For example, lower stormwater runoff means drainage networks and detention basins can be smaller and will require less maintenance. Also, reduced stormwater runoff means reduced contaminant loads can be transported to natural waterways, which will preserve water quality in many urban areas.

CONCLUSIONS

This study has highlighted that at the allotment scale and in the cities studied, there is more than enough water to satisfy water demand and that decentralized approaches, climatic regime and water demand significantly impact on mains water savings and stormwater runoff. Of the IWCM options considered, the use of water efficient appliances alone provided on relatively small mains water savings and no reductions in stormwater runoff. In comparison the DM + RWT strategy significantly increased mains water savings and reduced stormwater runoff.

The continuous simulation of rainwater tank drawdown in conjunction with intra-daily rainfall and water demand provided a realistic model of rainwater tank storage available for intra-daily rainfall entering the tank and water demand leaving the tank. As a result, the influence of climatic regime and water demand on the efficacy of the selected IWCM options was highlighted.

The selection of locations with different climatic regimes gave insight into the detailed processes that contribute to designing optimal urban water systems. However, results would be expected to vary with the use of smaller and larger rainwater tanks, smaller and larger roof areas and lower and higher water demands, particularly with respect to the relationships observed between IWCM options, water demand and roof area at each location. Continuous simulation allows intra-daily rainwater tank configuration to be determined, providing the necessary insight to evaluate rainwater harvesting under different climate regimes and water demands. Results from this study provide compelling evidence for the implementation of decentralized, allotment scale IWCM options, particularly rainwater tanks, in the sustainable management of catchment water resources under increased pressure from increasing populations and climate change.

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