RAINWATER TANK OPTIONS FOR STORMWATER MANAGEMENT IN THE UPPER PARRAMATTA RIVER CATCHMENT

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Abstract

This study investigates the extent to which rainwater tanks reduce the amount of on-site stormwater detention (OSD) storage required to satisfy the Upper Parramatta River Catchment Trust's (UPRCT's) OSD policy. In view of the limitations of the design storm approach, a continuous simulation approach was adopted. The DRIP stochastic rainfall model was linked with an allotment water balance model to evaluate different allotment scenarios using a 1000-year synthetic pluviograph record. The DRIP model was calibrated to a 53-year pluviograph located at Ryde. Comparison with statistics not used in calibration showed that DRIP performed satisfactorily. In particular good agreement with observed intensity-frequency-duration (IFD) curves was obtained, whereas AR&R IFD curves consistently underestimated the observed IFDs. Scenarios involving combinations of OSD, using 10kL rainwater tanks with 0 and 5 kL of detention storage were examined. For allotments with single dwellings between 50 to 70% of the tank volume can be counted towards the allotment's OSD volume. For a townhouse development this percentage varied between 36% and 53%. Rainwater tanks used in the single dwelling and townhouse scenarios are expected to reduce mains water consumption by 39% - 30% and 32% - 27% respectively. The variation depends on the number of occupants and the amount of tank airspace reserved for detention storage and the fraction of allotment drained by the rainwater tank(s).

Key words: rainwater tanks, on-site detention, stormwater management, continuous simulation

Introduction

On-site stormwater detention (OSD) storage is a source control measure widely used to ameliorate the hydrologic effect of urban development. There is growing interest and acceptance for the use of rainwater tanks to reduce the demand on mains water infrastructure. Rainwater tanks also provide stormwater benefits. The airspace above the tank overflow provides detention storage. In addition, a rainwater tank that is being used to supply indoor uses such as toilet flushing and hot water supply and outdoor uses will experience continual drawdown. As a result, at the beginning of a storm, the tank water level may be well below the overflow level providing valuable retention storage (that is, rainwater which is retained on site for use).

This study investigates the efficacy of rainwater tanks to reduce OSD storage. In particular it investigates the extent to which rainwater tanks reduce the amount of on-site stormwater detention (OSD) storage required to satisfy the Upper Parramatta River Catchment Trust's (UPRCT's) policy.

The design storm approach recommended by Australian Rainfall and Runoff (AR&R) [Institution of Engineers, Australia, 1987] is intrinsically incapable of performing such an assessment because the state of the rainwater tank at the commencement of the design storm is unknown. Indeed this is the Achilles heel of the design storm approach in general. It is now accepted that a design storm typically represents a burst of extreme rainfall embedded in a longer storm event (Walsh et al., 1991; Srikanthan and Kennedy, 1991; Hill and Mein, 1996; Coombes, 2002). The pre-burst rainfall may significantly affect the performance of the rainwater tank during the design burst. The only feasible and rigorous approach is to use continuous simulation.

In pursuit of this objective the DRIP event rainfall model (Heneker et al., 2001) was linked with the allotment water balance model described by Coombes and Kuczera (2001). The allotment model simulates consumptive use of mains and raintank water as well as stormwater dynamics.
The DRIP point rainfall model was calibrated to a medium-length pluviograph record at West Ryde and a synthetic 1000-year pluviograph record representative of the UPRCT area was generated. The synthetic pluviograph was subjected to a range of tests including comparisons with AR&R IFD curves.

The performance of rainwater tank and on-site detention options was evaluated for four allotment scenarios using the 1000-year synthetic pluviograph record.

Generation of a Synthetic Pluviograph Record

A 1000-year synthetic pluviograph series was generated for the Ryde Pumping Station raingauge location near the UPRCT catchment using the event-based rainfall model DRIP. The Ryde PS gauge proved to be the only pluviometer with an adequate medium length record (of the order of 50 years) in or near the UPRCT catchment.

The synthetic series were validated using a variety of rainfall statistics not used in the calibration. In addition DRIP-simulated IFD curves were compared against those produced by AR&R. A brief discussion of differences is presented.

The DRIP model

DRIP (Disaggregated Rectangular Intensity Pulse) is a stochastic rainfall simulation package currently under development at the University of Newcastle and the University of Adelaide. The DRIP model is event-based and is capable of representing the inter-event time, storm duration, average event intensity and the within-storm temporal characteristics of point rainfall. It can be used to simulate long sequences of rainfall events at time-scales down to less than 6 minutes. DRIP is able to satisfactorily reproduce rainfall statistics important in urban design given a long length pluviograph. A full description of DRIP can be found in Heneker et al. [2001].

The current version of DRIP incorporates a hidden state Markov model to simulate the occurrence of dry and wet climate states. Frost et al. [2000] show that storm characteristics are different between the dry and wet climate states. They demonstrate that inclusion of a hidden state Markov model is necessary to be able to reproduce annual rainfall statistics. The preferred method for calibrating DRIP is to use a long-term pluviograph record at the site of interest.

DRIP calibration to Ryde Pumping Station pluviograph

The longest pluviograph record in the Sydney metropolitan area is located at Observatory Hill Sydney. However, in view of the strong dependence of seasonal rainfall statistics on the distance from the coast, it was considered the Observatory Hill record may not be representative of sites within the UPR catchment. Therefore, it was decided to directly calibrate DRIP to a medium length pluviograph record considered to be more representative of the UPRCT area. In the search for a suitable site UPRCT provided the list of pluviograph sites, located within 10 km of Toongabbie, the centre point of the UPRCT area. From this list Ryde Pumping Station gauge was chosen for two reasons:

1. It had the longest record, namely 53 years.
2. Despite the fact that it is located outside the UPRCT area in a region with higher rainfall intensities, it is located sufficiently far from the coast to have annual rainfall statistics similar to those at Parramatta.

The Ryde PS gauge is operated by Sydney Water. The data was provided by Australian Water Technologies.

Validation

The DRIP model was calibrated to the 53 years of pluviograph data available at Ryde PS. Validation plots for the DRIP simulation are shown in Figures 1 and 2. It is important to note that these plots present rainfall statistics not used in the calibration.

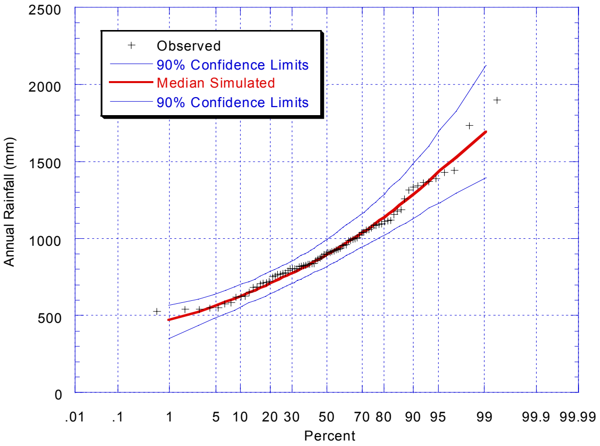

Figure 1. Ryde observed annual rainfall versus DRIP simulation

Figure 1 shows that observed annual rainfall is reproduced well by DRIP simulation. It is noted that the annual distributions for Ryde and Parramatta are similar. More importantly for this study, the DRIP simulation satisfactorily reproduces the short timescale aggregation statistics such as daily and hourly means and standard deviation.

Although the simulated aggregation statistics match the observed values well, extreme rainfalls on timescales from around 15 minutes to 6 hours

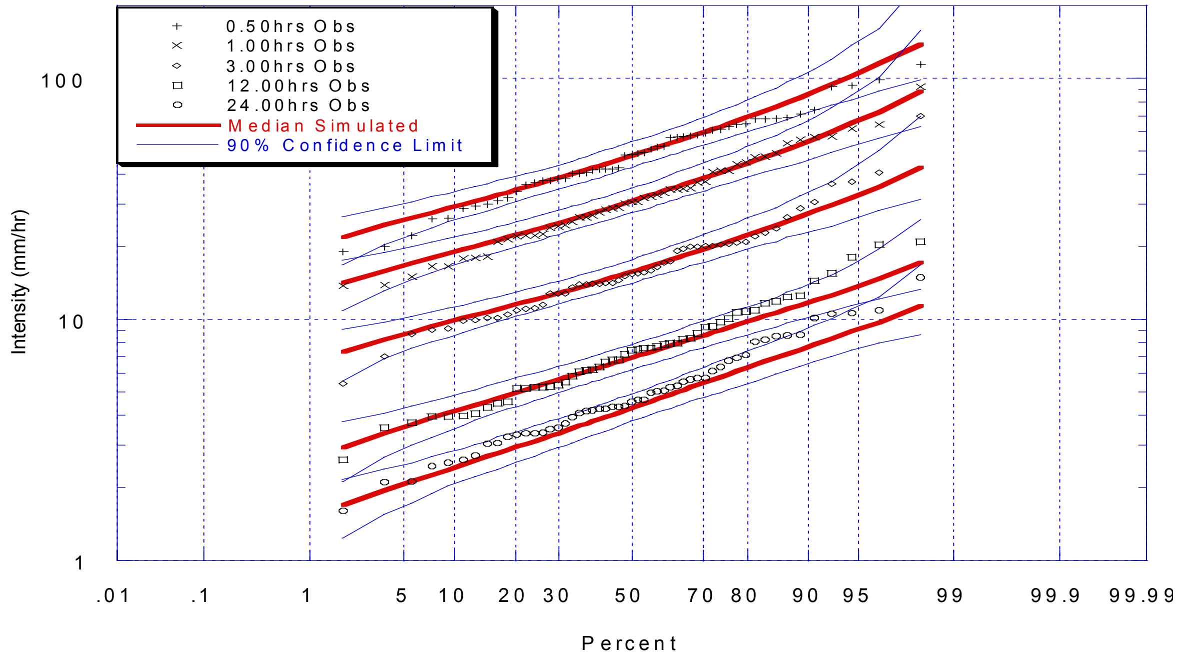

Figure 2. Ryde observed versus simulated DRIP IFD curves.

are of most importance to this study. Therefore, the simulated IFD curves for a range of durations were compared to those observed in Figure 2. Given that the DRIP was not calibrated to the IFD statistics the results are good, with the observed IFD statistics lying within the 95% confidence limits for all durations but the 12 and 24 hour curves, which show minor departures outside the 95% limits.

Comparison with AR&R IFD

Design IFD curves calculated using the methods described in AR&R can be used to provide a check against simulated values. Figure 3 compares the observed, median DRIP simulated and AR&R IFD curves for a range of timescales.

Figure 3 shows that the AR&R IFD curves underestimate the observed IFD statistics at Ryde in the right tail. This appears to be due to consistent underestimation of the log-standard deviation (which is the slope of the IFD curve on log-normal probability paper) rather than due to shifts in log skewness. The observed IFD curves show only weak evidence of non-zero log skew, which is consistent with the data at Observatory Hill Sydney. The consistent underestimation by

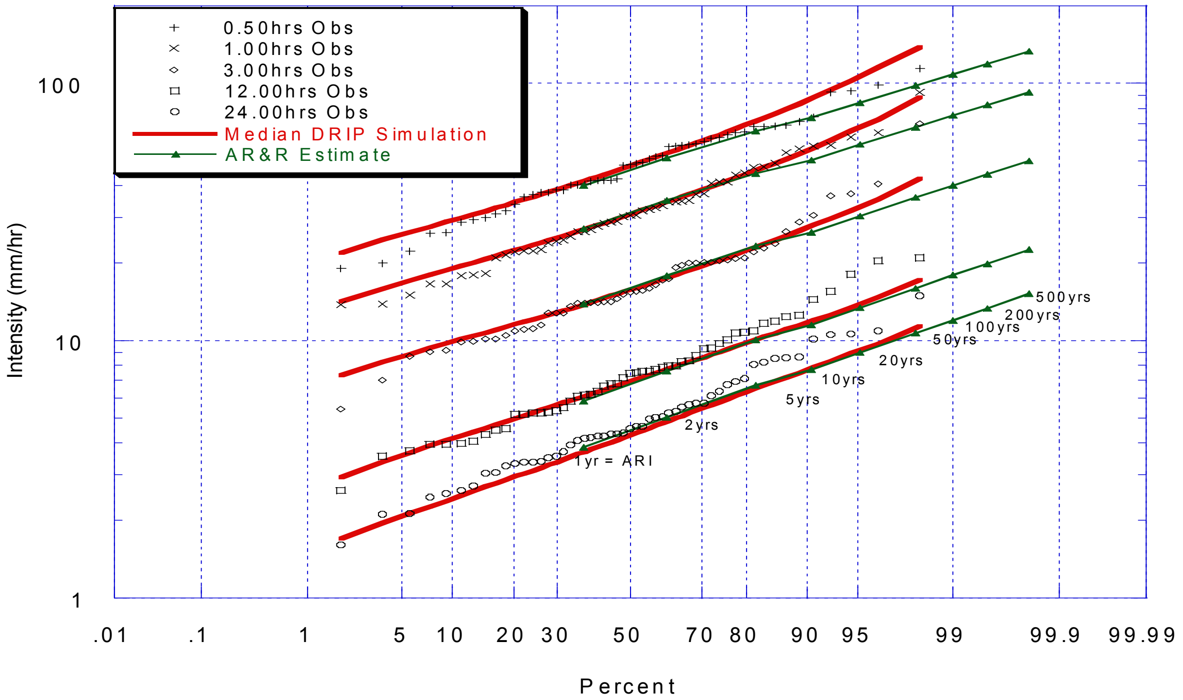

Figure 3. Ryde observed versus simulated DRIP versus AR&R IFD curves.

AR&R is due to two factors:

1. The AR&R IFD curves are derived from a regional procedure that spatially interpolates between gauge locations with good record lengths. Regionalisation, by its nature, smoothes spatial variability and hence can introduce systematic error.
2. The AR&R curves were derived from a database ending in the late 1970s and early 1980s. This database had a good coverage of 24-hour bulk gauges but few long-term pluviograph records in the Sydney area. With the availability of up to 20 years more data it is probable, indeed expected, that differences will arise, particularly in the right tail of the IFD curve.

OSD and Rainwater Tank Performance

The allotment water balance model developed by Coombes and Kuczera (2001) simulates consumption of main and raintank water and stormwater dynamics over the allotment at appropriate time scales. 1000 years of continuous simulation using the synthetic Ryde PS record was input to the allotment model for two case studies. The case studies were developed to analyse the performance of rainwater tanks in combination with the UPRCT on-site detention (OSD) policy. The developments are assumed to be on a clay soil type.

For each case study the performance of the UPRCT OSD policy along with two rainwater tank scenarios with and without detention storage was considered. Two rainwater tank options were considered for each case study. One scenario (10R) used a 10 kL rainwater tank with no airspace for detention (Figure 4). The other rainwater tank scenario (10R+A) used a 10 kL rainwater tank with a 5 m^3 airspace for detention and an outlet with a 30 mm diameter orifice (Figure 5).

Note that average recurrence intervals (ARIs) derived from discharges generated in continuous simulation are a product of entire storms rather than the storm bursts described in AR&R. The rainfall input to the water balance model was a synthetic pluviograph rainfall record simulated using DRIP calibrated to the Ryde Pumping Station. The UPRCT's on-site detention policy requires a storage volume of 470 m^3 per ha and a permissible site discharge (PSD) of 80 L/s per ha of land area. The OSD scenario for each development case is designed in accordance with the On Site Detention Handbook [UPRCT, 1999]. All stormwater runoff from roofs, impervious and pervious areas is directed to the OSD tanks.

The rainwater tank scenario for each development assumes that rainwater from tanks is used to supply hot water, toilet and irrigation uses. Mains water is used to top up the rainwater tanks at a rate of 18 litres per hour in dry periods and for household uses not supplied with rainwater.

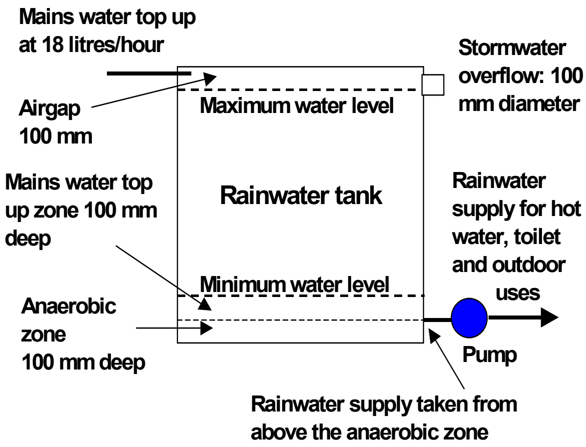

Figure 4. Design details of the rainwater tank without an airspace for detention (10R)

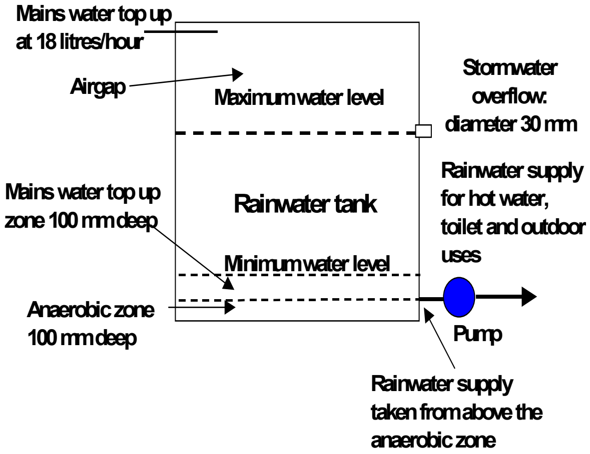

Figure 5: Design details for a rainwater tank with a 5 m^3 airspace for detention (10R+A)

Water use

The allotment model simulates consumptive use of mains and raintank water. The purpose of this simulation is to determine the depth of water in the rainwater tank (and other on-site storages) at the start of a storm.

A linear regression was developed to estimate average daily household water use for each month of the year for the Parramatta region using climate, socio-economic and water use data from the Lower Hunter Region zones (Coombes and Kuczera, 2001). The monthly daily average indoor water use (litres/day) is:

$$\mathrm{inDem} = 27.79 + 145.69\mathrm{P} - 0.422\mathrm{M} - 10.579\mathrm{AveR} + 6.74\mathrm{AveRdays} - 0.162\mathrm{Inc} - 12.28\mathrm{G} + 0.49\mathrm{AveTemp} \quad (1)$$

where P is the number of occupants in the dwelling, M is a seasonal index ranging from 1 to 6, Inc is average weekly income per person ($), AveR is the average of the monthly daily average rainfall, AveRdays is the mean of the number of rain days in a month, G is annual population growth (%) and AveTemp is the mean of the monthly daily average temperature (°C). Equation (1) yielded a R^2 value of 0.81.

The monthly daily average outdoor water use (litres/day) is:

$$\mathrm{exDayDem} = -251.5 + 7.53\mathrm{M} - 11.3\mathrm{AveR} - 0.025\mathrm{Inc} - 0.816\mathrm{AveRdays} + 24.44\mathrm{G} + 19.08\mathrm{AveTemp} \quad (2)$$

Equation (2) yielded a R^2 of 0.69. The estimated average daily water use for the Parramatta area is shown in Table 1.

Table 1. Estimated average daily household water use for the Parramatta area

	Average water use (Litres per day)					
	Outdoor	Inhouse (number of occupants)				
Month		1	2	3	4	5+
January	206	166	312	457	603	749
February	209	158	304	450	595	741
March	206	167	312	458	604	749
April	180	149	294	440	586	731
May	141	167	312	458	604	749
June	103	160	306	451	597	743
July	111	155	301	447	593	738
August	152	151	297	442	588	734
September	184	153	299	444	590	736
October	222	164	310	455	601	747
November	250	165	310	456	602	747
December	294	162	307	453	599	744

The data in Table 1 were used to calibrate a behavioural model of outdoor domestic daily consumption which simulates the high climate-dependant variability of outdoor water use. A diurnal profile was used to disaggregate daily water use to shorter time scales.

The single dwelling scenario

The single dwelling scenario consists of a 600 m^2 allotment, a house with a roof area of 150 m^2 and a paved surface area of 200 m^2 (Figure 6). Applying the OSD rules from the UPRCT On-Site Detention Handbook to this site results in a site storage volume of 28.2 m^3, a 48 mm diameter orifice plate outlet to provide a permissible site discharge (PSD) of 0.0048 m^3/s to the street drainage system.

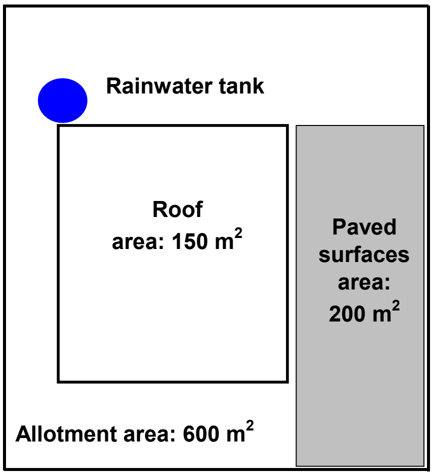

Figure 6: Single dwelling scenario

Stormwater peak discharges from the allotment for the OSD, 10R and 10R+A scenarios are reported in Table 2 for 1, 2, 5 and 100 year ARIs. The OSD scenario is shown to significantly reduce peak discharges, although the maximum allowable peak discharge prescribed by the On-site Detention Handbook was exceeded for all ARIs greater than 63 years. The rainwater tank scenarios significantly reduced peak discharges for the 1 and 2 year ARIs, but were ineffective for higher ARIs.

Table 2. Peak discharges from the allotment

Scenario	**Peak discharge (m^3/s) at ARI (years)**			
	1	**2**	**5**	**100**
No OSD	0.009	0.032	0.056	0.165
OSD	0.001	0.002	0.003	0.049
10R	0.005	0.025	0.05	0.162
10R+A	0.005	0.021	0.043	0.156

Table 3 presents for the OSD and rainwater tank scenarios the OSD volumes required to ensure that there are no significant overflows from the allotment up to the 100 year ARI. These volumes were found using a search algorithm. A significant overflow is defined as a volume of stormwater greater than 2 mm times the site area. The scenarios examined include rainwater tanks used to supply hot water, toilet and outdoor uses, rainwater tanks used to supply outdoor uses only, and households with 3 and 5 occupants.

The percentage of rainwater tank volume that can be counted as part of the overall site OSD storage volume when the rainwater tank is used for hot water, toilet and irrigation is shown in Table 4. The average percentage of rainwater tank volume that can be counted as OSD storage volume is 55% for the rainwater tank with no airspace for detention and 70% for the rainwater tank with half of its volume for airspace.

Table 3: OSD storage requirement for different scenarios

Scenario	OSD storage requirement (m^3)		
	Hot water, toilet and outdoor uses		Outdoor use only
	3 people	5 people	
OSD	55	55	55
10R+OSD	50	49	54
10R+A+OSD	48	48	53

Table 4: Percentage of rainwater tank volume contributing to OSD storage volume

Scenario	Occupants	OSD Storage (%)
10R	3	50
10R	5	60
10R+A	3	70
10R+A	5	70

The rainwater tank scenarios revealed insignificant peak discharge reduction from the allotment and small reductions in OSD site storage requirement for all ARIs greater than 2 years. The reason for this result is simple. Rainwater tanks only intercept roof runoff whereas all stormwater runoff from the roof, pervious and impervious areas is directed to the OSD tank that also provided more storage space than the rainwater tank prior to the annual maximum storms.

However, focussing on peak discharge obscures a significant benefit attributable to rainwater tanks. Figure 7 compares the hydrographs from a typical annual maximum storm event for three scenarios. The OSD tank scenario is shown to have a significantly lower peak discharge than the two rainwater tank scenarios. However, the important result is the difference between the volumes of the hydrographs. The rainwater tank reduces the volume of surface runoff discharging from the allotment to the catchment, whereas the OSD solution does not reduce stormwater runoff volumes. The rainwater tank provides retention as well as detention storage, while the OSD tank only provides detention storage. Water levels in rainwater tanks used to supply domestic toilet flushing, outdoor and hot water uses are constantly drawn down. This ensures that the rainwater tank regularly has storage capacity available to accept roof runoff resulting in reduced mains water use and stormwater discharge.

The importance of reducing stormwater runoff volumes rather than peak discharges from individual allotments for stormwater management in catchments has not been apparent to the stormwater industry. Many authors such as Argue et al. (2000), and Andoh et al. (1999) report that the cumulative effect of volume reduction provided by site retention techniques such as infiltration measures and rainwater tanks more than compensates for the higher peak discharges from individual sites on catchments.

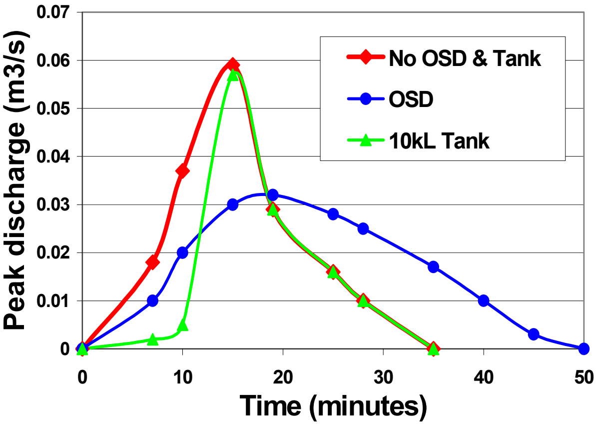

Figure 7. Hydrographs of stormwater discharge from rainwater tanks and OSD from a single storm event

Analysis of urban subdivisions by Coombes et al. (2000 and 2000a) revealed that the use of source control measures including rainwater tanks produced substantial peak discharge reductions from the subdivided catchment that will reduce the need for centralised stormwater infrastructure. A summary of these results is presented in Kuczera and Coombes (2001). An analysis of the performance of a subcatchment that contains rainwater tanks on individual allotments will be required to determine the larger-scale benefits of different sized rainwater tanks.

Other benefits are attributable to the rainwater tank scenarios. The use of rainwater tanks resulted in 39% and 30% reductions in mains water use for the 10R and 10R+A scenarios.

The Townhouse Development Case Study

The townhouse case study, illustrated in Figure 8, consists of 9 double storey townhouses with roof areas of 98 m^2 each and paved surfaces with an area of 519 m^2 situated on an allotment with an area of 1858 m^2. Applying the UPRCT OSD rules to this site results in a site storage volume of 87.3 m^3 and a 110 mm diameter orifice plate outlet which provide a PSD of 0.015 m^3/s to the street drainage system.

Stormwater peak discharges from the townhouse development for the different scenarios are reported in Table 5. The OSD scenario is shown to reduce peak discharges, although the maximum allowable peak discharge prescribed by the UPRCT OSD policy was exceeded for all ARIs greater than 22 years.

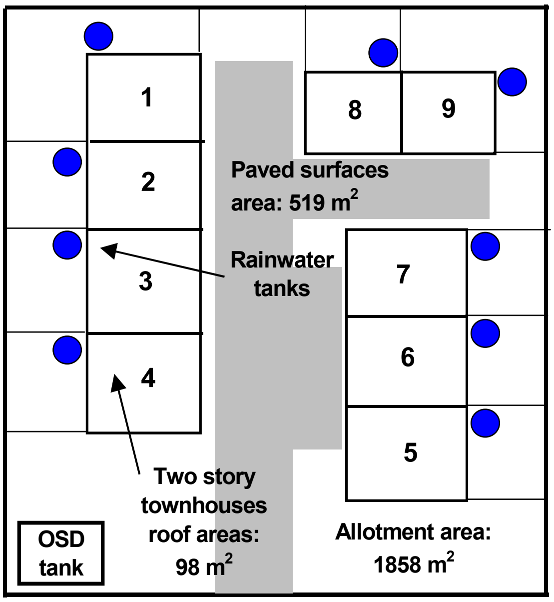

Figure 8. Schematic of the townhouse development.

Table 5. Peak discharges from the allotment

Scenario	Peak discharge (m^3/s) at ARI (years)			
	1	2	5	100
No OSD	0.043	0.123	0.197	0.528
OSD	0.008	0.015	0.018	0.311
10R	0.012	0.058	0.119	0.494
10R+A	0.002	0.024	0.065	0.480

The rainwater tank scenarios exhibited large reductions in peak discharges below that from a townhouse development with no OSD and rainwater tank storage. The greatest reductions occur for ARIs up to 2 years, but the reductions remain appreciable even for large ARIs. Nonetheless, stormwater discharges from the rainwater tank scenarios are dominated by discharges from the impervious areas not connected to the rainwater tanks. In combination with a policy to minimise impervious areas directly connected to the street drainage system the use of rainwater tanks could produce equivalent stormwater management results to the current UPRCT OSD policy.

Annual maximum peak discharges from the townhouse development beyond the 2 year ARI are dominated by discharges from the impervious area (591 m^2) not managed by the rainwater tanks. Roof areas in the townhouse development occupy a greater proportion of the site area than the roofs in the single dwelling case study. The improved performance of the rainwater tank scenarios results from a greater proportion of the site area connected to rainwater tanks and an accumulation of detention and retention storages.

Table 6 presents for the OSD and rainwater tank scenarios the OSD volumes required to ensure that there are no significant overflows from the allotment up to the 100 year ARI.

Table 6. OSD storage requirement for different scenarios

Scenario	OSD storage requirement (m^3)		
	Hot water, toilet and outdoor uses		Outdoor use only
	3 people	5 people	
OSD	165	165	165
10R+OSD	133	131	138
10R+A+OSD	119	117	123

The percentage of rainwater tank volume that can be counted as part of the overall site OSD storage volume when the rainwater tank is used for hot water, toilet and irrigation is shown in Table 7.

Table 7. Percentage of rainwater tank volume contributing to OSD storage volume

Scenario	Occupants	OSD Storage (%)
10R	3	36
10R	5	38
10R+A	3	51
10R+A	5	53

From Table 7 the average percentage of rainwater tank volume that can be counted as OSD storage volume is 37% for the rainwater tank with no airspace for detention and 52% for the rainwater tank with half of its volume for airspace. In addition, the use of rainwater tanks resulted in 32% and 27% reductions in mains water use for the 10R and 10R+A scenarios.

Conclusions

In view of the fundamental limitations of the design storm approach, continuous simulation was used to evaluate the contribution of rainwater tanks to manage stormwater runoff from allotments located in the Upper Parramatta River Catchment. The DRIP point rainfall model was calibrated to 53 years of pluviograph data at Ryde Pumping Station. The DRIP model was shown to adequately reproduce statistics not used its calibration including IFD curves. It was found that AR&R IFD curves consistently underestimated the observed IFD curves.

DRIP was used to generate 1000 years of pluviograph data which was input to the allotment water balance model that was used to examine scenarios involving combinations of OSD, 10kL rainwater tanks with 0 and 5 kL of detention storage.

For allotments with single dwellings between 50 to 70% of the tank volume can be counted towards the allotment's OSD volume and a 39% to 30% reduction in mains water use was expected. For a townhouse development this percentage varied between 36% and 53% and a 32% to 27% reduction in mains water use was expected. The variation depends on the number of occupants and the amount of tank airspace reserved for detention storage and the fraction of allotment drained by the rainwater tank(s). As the number of occupants increases, the rate of drawdown in the tank increases, making more retention storage available on average at the beginning of a storm.

Focussing on peak discharges at the allotment scale may obscure the true benefits of rainwater tanks for stormwater management. Rainwater tanks reduce volumes of stormwater discharged into the larger catchment, whereas OSD tanks merely detain the stormwater. The cumulative effect of volume reduction provided by rainwater tanks may more than compensate for the higher peak discharges from individual allotments. The stormwater hydrograph from larger catchments may be more sensitive to runoff volume reductions from subcatchments than short delays in subcatchment runoff.

The current practice of modelling distributed storage or detention devices within a catchment as a single entity at the centroid of a catchment may produce misleading results. It is recommended that the industry undertake a studies to analyse the stormwater performance of catchments in which OSD and rainwater tanks are distributed according to their actual location within the catchment.

Acknowledgement

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