Impact of Rainwater Tank and On-site Detention Options on Stormwater Management in the Upper Parramatta River Catchment

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For

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SUMMARY

The principal objective of this study is to determine by how much do rainwater tanks reduce the amount of on-site stormwater detention (OSD) storage required to satisfy Upper Parramatta River Catchment Trust's (UPRCT) policy. In pursuit of this objective four tasks were performed:

- Calibrate the DRIP point rainfall model to a pluviograph record at Parramatta.
- Using DRIP generate a synthetic 1000-year pluviograph record representative of the Upper Parramatta River (UPR) catchment.
- Modify an existing allotment water balance model to include OSD storage.
- Evaluate using continuous simulation the performance of a range of rainwater tank and on-site detention options for several allotment scenarios over a 1000-year synthetic pluviograph record.

Drip rainfall model calibration and validation

The DRIP point rainfall model underpins this study because the rainfall regime is the primary factor controlling OSD outcomes. Hence its calibration and validation are key tasks. Several key findings arose from the calibration and validation of DRIP:

1. It was originally envisaged that DRIP would be directly calibrated to a long pluviograph at Parramatta. However, owing to the very short pluviograph record at Parramatta this approach was deemed infeasible and an alternative approach was developed.

2. DRIP was directly calibrated to the 53-year Ryde Pumping Station pluviograph record. The Ryde record was the longest available record for gauges located in and near the UPR catchment. The calibrated model was used to simulate statistics not used in the calibration. Such statistics ranged from annual rainfall distributions to IFD curves. For all the validation statistics considered, DRIP simulations were found to be statistically consistent with the observed statistics. This result engendered confidence in DRIP's ability to simulate the entire rainfall regime from very short to annual timescales.

3. It was found at Ryde that both the DRIP and observed IFD curves produced short duration 100-year intensities about 25% greater than those predicted by AR&R. Examination of observed IFD curves for Guildford showed similar underestimation by AR&R, whereas for Bankstown AR&R IFD curves unsatisfactorily reproduced the overall shape of the observed IFD curves but did manage to reproduce the right tails better than at Ryde or Guildford. It is difficult to avoid the conclusion that the AR&R IFD curves are in significant error and need revision.

4. The Ryde pluviograph can be used as a master site to transfer DRIP to other shorter pluviograph records within the UPR catchment. The justification for use of the Ryde record as the master site in future work is that it has a similar annual rainfall distribution as Parramatta, is similarly distant from the coast, and has AR&R IFD statistics that only marginally differ across a range of sites in the UPR catchment.

OSD and rainwater tank performance

Using an allotment water balance model purposely modified for this study, 1000 years of continuous simulation using the synthetic Ryde record was undertaken for four case studies at the allotment scale: Single dwelling; duplex; townhouse and apartment developments.

For each case study the performance of the UPRCT OSD policy along with various rainwater tank scenarios with and without detention storage was considered.

Table A summarizes the performance of UPRCT's OSD policy for different allotment scenarios.

Table A. Performance of UPRCT OSD policy.

Allotment scenario	Impervious fraction (%)	Total area (m^2)	UPRCT OSD storage (m^3)	PSD L/s	ARI at which PSD is exceeded	OSD storage for PSD to be exceeded at 100 yr ARI (m^3)
Single dwelling	58	600	28.2	4.8	63	55
Duplex	83	600	28.2	4.8	12	67
Townhouse	75	1858	87.3	14.9	22	165
Apartment	67	1200	56.3	9.6	15	119

Three important findings are noted:

1. The PSD is exceeded for ARIs well below 100 years. An exceedance was defined as an overflow event in which the volume of stormwater was greater than 2 mm times the allotment area. A corollary of this is that the OSD storage requirement to achieve compliance with the 100 year PSD is almost double that of the UPRCT's current OSD requirement.

   It is noted that these results are highly sensitive to the choice of time of concentration. In this study a time of concentration of 2 minutes was adopted to be consistent with the experimental observations of Stephens and Kuczera (1999). If the widely used time of concentration of 5 minutes were adopted the complying OSD volume reduces from 55 m^3 to 29 m^3 for a single dwelling allotment. However, the authors cannot find experimental evidence in support of the 5 minute value and therefore did not consider it.

2. The PSD depends on the allotment type and impervious fraction. It is suggested the OSD policy discriminate according to allotment type and its impervious fraction.

The effectiveness of rainwater tanks as a stormwater management measure was found to increase with housing density. As the proportion of the allotment area (roofs) contributing to the rainwater tank increased the peak allotment discharge for a given ARI decreased further below the peak discharge for an allotment with no OSD or rainwater tanks.

Rainwater tanks used to supply in-house uses were found to have storage volumes available for stormwater retention at the beginning of over 90% of annual maximum storm events. In combination with a policy to manage or limit directly connected impervious areas rainwater tanks could produce similar stormwater management performance as the current UPRCT OSD policy.

The average percentage of rainwater tank volume that can be counted as OSD site storage is presented in Table B for each allotment scenario.

Table B. Average percentage of rainwater tank volume that can be counted as OSD site storage

	Volume of rainwater tank counting as OSD storage (%)	
Scenario	No airspace in tank	50% airspace in tank
Allotment	42	65
Duplex	50	72
Townhouses	40	53
Walk up apartments	32	51

The rainwater tank scenarios in which no air space was provided for stormwater detention demonstrated a reduction in required OSD storage volume equivalent to about 41% of the rainwater tank capacity. In contrast, the rainwater tank scenarios with air space for stormwater detention demonstrated a reduction in required OSD storage volume equivalent to 60% of the rainwater tank capacity.

The averages presented in Table B are indicative of the rainwater tank contribution to OSD storage. The actual OSD contribution of rainwater tanks depends on the tank volume, the inclusion of airspace and the allotment type. It is recommended that the site-specific values presented in Tables 12, 17, 22 and 27 be used.

The true benefits of rainwater tanks for stormwater management may be obscured by focussing on peak discharges at the allotment scale. Rainwater tanks reduce volumes of stormwater discharged into the larger catchment, whereas OSD tanks merely detain the stormwater. It is recommended that the UPRCT undertake a study to analyse the stormwater performance of catchments in which OSD and rainwater tanks are distributed according to their actual location within the catchment.

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1. INTRODUCTION

The Upper Parramatta River Catchment Trust (UPRCT) commissioned the authors to determine by how much do rainwater tanks reduce the amount of on-site stormwater detention (OSD) storage required to satisfy UPRCT's policy. UPRCT required that continuous simulation be used to evaluate the performance of the rainwater tanks. The rationale for using continuous simulation arises from the intrinsic limitation of the design storm approach to specify initial conditions. It is now accepted that a design storm typically represents a burst of extreme rainfall embedded in a longer storm event. The pre-burst rainfall may significantly affect the performance of the rainwater tank during the design burst. Only continuous simulation can rationally simulate these complex dependencies.

In pursuit of this objective UPRCT requested four tasks be performed with the aid of models currently under development in the hydrology research program at the Department of Civil, Surveying and Environmental Engineering at the University of Newcastle:

- Calibrate the DRIP point rainfall model to a pluviograph record at Parramatta.
- Using DRIP generate a synthetic 1000-year pluviograph record representative of the Upper Parramatta River (UPR) catchment.
- Modify the allotment water balance model to include OSD storage.
- Evaluate the performance of a range of rainwater tank and on-site detention options for several allotment scenarios using the 1000-year synthetic pluviograph record.

This report is organised as follows:

- Section 2 describes the application of the DRIP point rainfall model. Owing to an inadequate pluviograph record at Parramatta, a revised methodology is implemented. Validation using statistics not used in the calibration is used to check the performance of the calibrated DRIP model. DRIP intensity-frequency-duration (IFD) curves are compared against Australian Rainfall and Runoff (AR&R) and observed IFD curves. A discussion of the results is presented followed by recommendations.
- Section 3 overviews design requirements for rainwater tanks emphasising the three zones for peaks mains demand reduction, rainwater storage and stormwater detention. Section 4 describes the cost models used to evaluate the economic performance of the various options.
- Section 5 provides an overview of the allotment water balance model.
- Section 6 presents the results of 1000 years of continuous simulation using the allotment water balance model for four case studies at the allotment scale: Single dwelling; duplex; townhouse and apartment developments. For each case study the performance of the UPRCT OSD policy is documented. In addition various rainwater tank scenarios with and without detention storage are considered. Combinations of OSD and rainwater tanks which ensure UPRCT's PSD is only exceeded with an ARI of 100 years are presented along with an economic analysis.

2. GENERATION OF A SYNTHETIC PLUVIOGRAPH RECORD

2.1 Introduction

A 1000-year synthetic pluviograph series was generated for two raingauge locations in the UPR catchment using the event-based rainfall model DRIP. UPRCT nominated the Parramatta gauge as representative of the study region. However, on account, of major limitations in the pluviograph record at Parramatta, the calibration approach was revised. Two independent approaches were implemented:

1. DRIP was calibrated using pluviograph data from Observatory Hill Sydney and a composite daily record based on the Parramatta and Parramatta North gauges.

2. DRIP was calibrated using pluviograph data from the Ryde Pumping Station gauge.

In both cases, the synthetic series were validated using a variety of rainfall statistics and were compared against Australian Rainfall and Runoff (AR&R) IFD curves. Following a comparison of the results a recommendation is made with regard to choice of calibrated model and extension of DRIP to other parts of the UPR catchment.

2.2 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. Unfortunately long-term pluviograph records often are not available.

In response to this problem, research currently underway at the Universities of Newcastle and Adelaide is investigating ways of regionalising DRIP. The most promising approach involves transfer of information from a long-term master pluviograph site to the target site. Two techniques have been developed and are currently being assessed for different Australian climate zones:

1. Transfer from the master site to a short (10 to 20 yrs) pluviograph record at the target site.

2. Transfer from the master site to a medium length (approx 50yrs) daily rainfall record at the target site.

2.3 DRIP Calibration To Parramatta: Regionalisation Approach

Owing to the short pluviograph record at Parramatta, direct calibration of DRIP was not possible. The only possible calibration strategy involves transfer from a master pluviograph site.

2.3.1 DRIP data requirements

DRIP calibration using the regionalisation approach involves two steps:

1. A long master pluviograph record at a site near the desired target site is used to calibrate DRIP.

2. A target site rainfall gauge is then used to calibrate scaling factors that scale the storm characteristics at the master site to reproduce those at the target site.

A schematic of this calibration process is shown below in Figure 1.

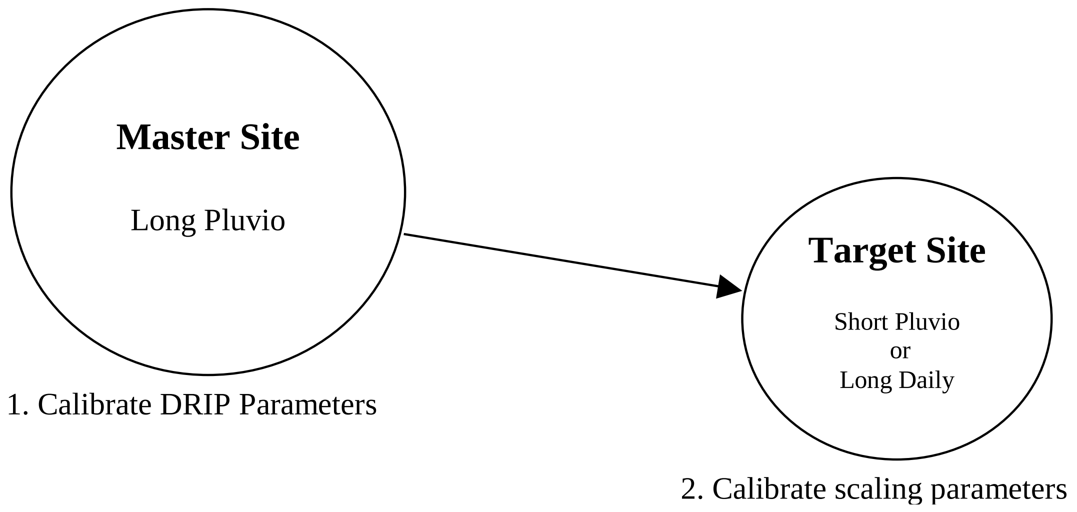


Figure 1. Drip calibration schematic

The scaling is defined as follows: Let x_M and x_T be random variables corresponding to the same rainfall characteristic at the master and target sites respectively. The rainfall characteristic may be storm duration, dry spell or average intensity conditioned on duration. The scaling factor α_k for a month k is defined as

$$x_T = \alpha_k x_M \quad (1)$$

The probability density function of x_T is given by

$$p_T(x_T) = \frac{1}{\alpha_k} p_M\left(\frac{x_T}{\alpha_k}\right) \quad (2)$$

where $p_M(\ )$ is the density of the master random variable.

2.3.2 Choice of sites

The master site chosen for this study was Observatory Hill Sydney (066062). This site was chosen due to the pluviograph's long length and its close proximity to the target Parramatta site. Indeed Observatory Hill Sydney has the longest pluviograph record in the Sydney region. This is important as there have been distinct dry and wet climate epochs. A short record may only sample climate variability from one climate state and hence bias the long-term extreme rainfall distributions.

At the target site, it would be ideal if there existed a pluviograph of sufficient length to be able to calibrate the scaling factors. However, the longest Bureau of Meteorology pluviograph within the Parramatta area (Parramatta North) contained less than three years of data. This was considered insufficient to calibrate the DRIP scaling parameters. Therefore daily rainfall records were used to calibrate the scaling parameters.

The use of daily records at the target site only allows calibration of the intensity and dry spell scaling factors. At Observatory Hill Sydney the average storm duration is of the order of 4 hours. As a result it is expected that the daily record contains virtually no information about storm durations. At this stage in the development of the DRIP regionalisation it is necessary to assume that the storm duration probability distribution is the same at the master and target sites; that is, the scaling factor for storm duration α_k=1 for all months.

Parramatta and Parramatta North daily rainfall records were the two obvious choices for the target site data. The Parramatta (066046) and the Parramatta North (066124) sites have continuous daily rainfall records spanning from 1909-1960 and 1965-1998 respectively. Due to the proximity of the sites, it was assumed that the daily distribution of rainfall was the same at both sites. Hence, the two records were added to one another to produce a single augmented Parramatta daily rainfall record to be used as the target site rainfall.

2.3.3 Sampling variability of validation statistics

Repeated simulation using the calibrated parameters was undertaken to quantify sampling variability for validation statistics. This is essential if validation statistics are to be meaningfully compared against DRIP statistics. DRIP simulated a record with the same length as the observed record 1000 times. For each replicate statistics of interest were extracted. The 1000 statistics were then ranked to obtain the median and 90% confidence limits. If the calibrated DRIP model is the correct model of the rainfall process, then there is a 90% chance that the observed statistic will fall within the simulated 90% confidence limits. In fact the 90% confidence limits should be wider than reported because uncertainty in the DRIP calibrate parameters is not accounted for in the current version.

In this report the DRIP model is judged not to be inconsistent with the observed data if the observed statistics lie within the 90% confidence limits. Note that because the DRIP model has not been calibrated to the validation statistics, median values do not necessarily follow the observed data.

2.3.4 Master site – Observatory Hill Sydney

The DRIP model was calibrated to the 87 years of pluviograph data available at Observatory Hill. Several validation plots for DRIP simulation at the master site are shown below in Figures 2,3 and 4.

Figure 2 shows that observed annual rainfall is reproduced well by the DRIP simulation. More importantly for this study, Figure 3 shows that short timescale aggregation statistics such as daily and hourly means and standard deviation are also reproduced by DRIP simulation quite well. Figure 4 compares observed and DRIP-simulated IFD curves. For the shorter durations a close match is found. However, for the 72-hour duration, the DRIP simulation produces a downward bias. This was considered unimportant for the current study because 72-hour durations are much greater than catchment response times - significant flooding is triggered by storm events lasting from around 15 minutes to 6 hours. Overall the DRIP simulation was considered to accurately reproduce the rainfall statistics apparent at the master site.

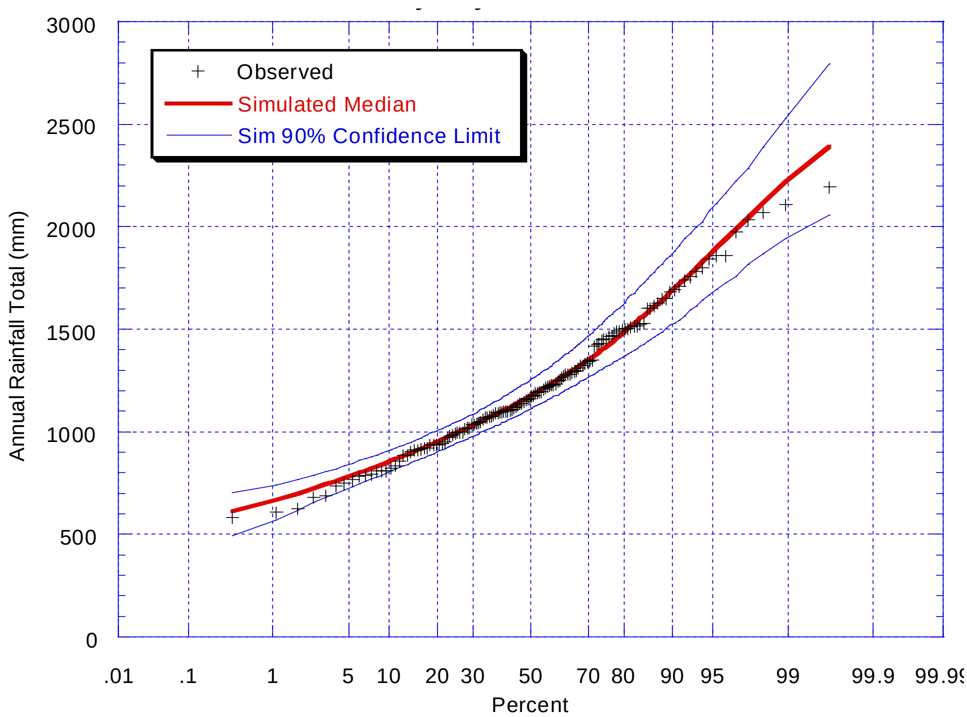


Figure 2. Sydney observed annual rainfall versus DRIP simulation

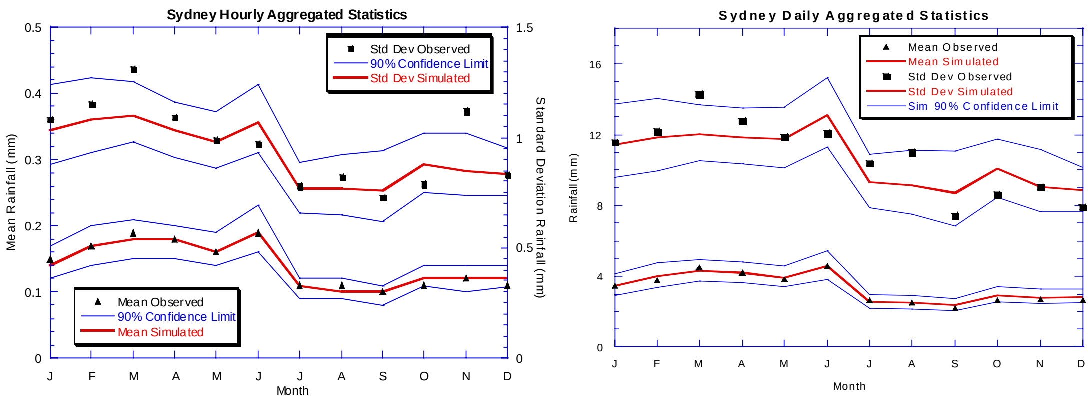


Figure 3. Sydney observed versus simulated (a) hourly and (b) daily mean and standard deviation of rainfall.

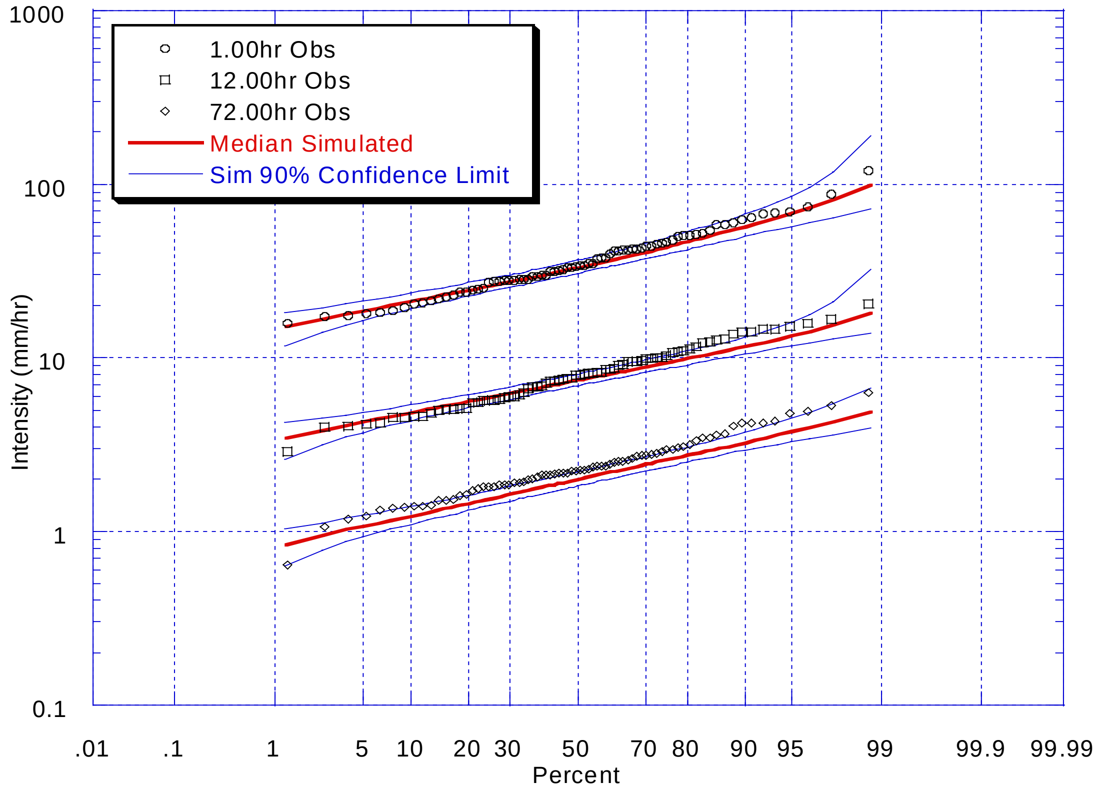


Figure 4. Sydney observed versus simulated intensity-frequency-duration curves

2.4.5 Target Site - Parramatta/Parramatta North

DRIP scaling parameters for dry spell and conditional average intensity were calibrated using the augmented Parramatta record. The scaling parameters produced were then used in a repeated DRIP simulation. Figure 5 shows a comparison between the simulated and observed annual rainfall totals.

Although the observed annual rainfall values do not lie on the simulated median curve, the majority of the observed values are within the 90% confidence limits for the model simulation. It is, therefore, concluded that DRIP adequately simulates the annual rainfall distribution at Parramatta..

Figures 2 and 5 highlight differences between the Observatory Hill Sydney and Parramatta locations. The Parramatta gauge has a median annual rainfall of the order of 950 mm whereas Observatory Hill Sydney has an annual median of about 1200 mm. This difference, attributable to coastal effects, forces one to question the assumption that the storm duration probability distributions are identical at both sites.

As there is no pluviograph of sufficient length in the Parramatta area, comparison of DRIP simulated statistics with observed variables with a timescale less than 24 hours was impossible. However, observed daily statistics could be calculated using the daily rainfall records.

Figure 6 compares the simulated daily means and standard deviations against those calculated from the augmented Parramatta daily record. The DRIP simulated median matches the observed daily mean for the majority of months. From September onwards DRIP slightly overestimates the daily mean, which can explain why the simulated annual rainfall is slightly overestimated in Figure 5. The simulated standard deviation of daily rainfall is not as accurate as the daily mean, with some observed values lying outside the confidence limits. Figure 7 shows a close match between the observed and simulated probabilities of a dry day.

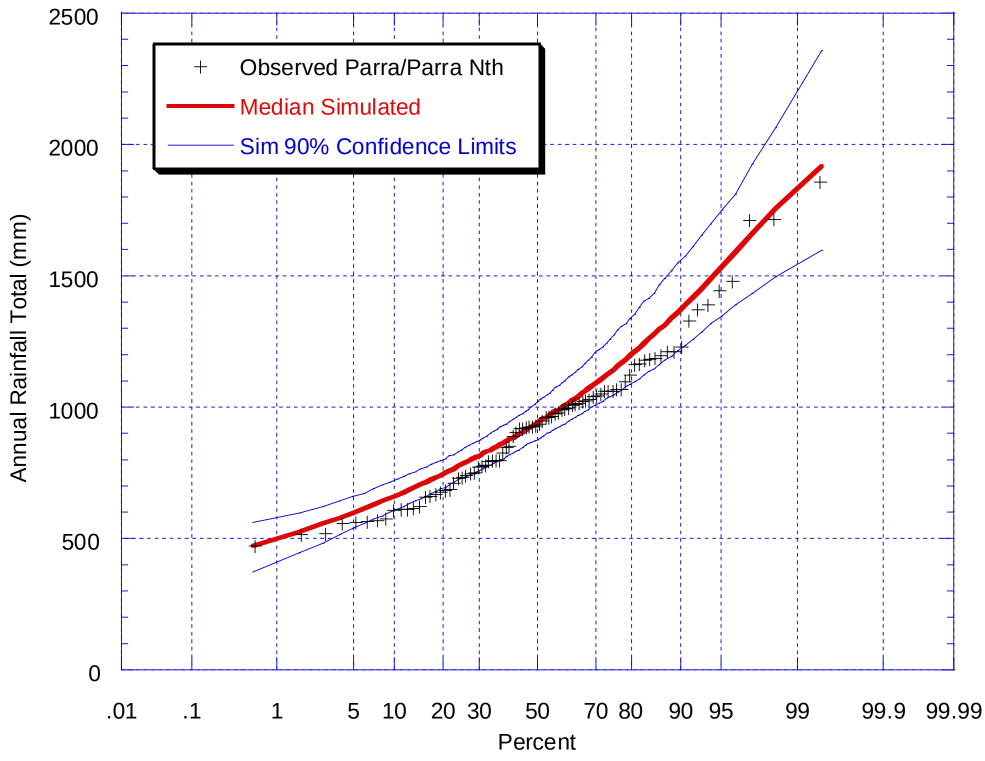


Figure 5. Parramatta observed versus simulated annual rainfall.

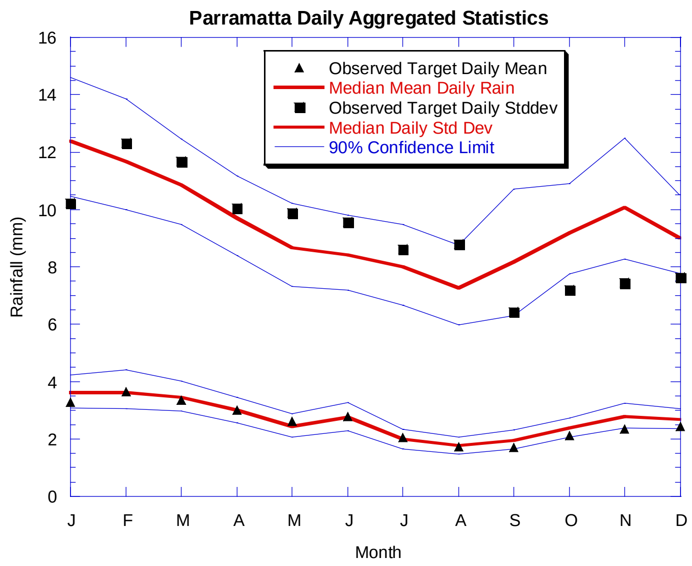


Figure 6. Parramatta observed vs simulated daily rainfall mean and standard deviation.

As mentioned previously, due to the lack of pluviograph data in the Parramatta area, observed statistics based on timescales less than 24 hours cannot be calculated. This presents a problem in validating the DRIP results on the timescales that are most important to this study, around 15 minutes to 6 hours. However, design IFD curves calculated using the methods described in

Australian Rainfall and Runoff (AR&R) can be used to provide a check against simulated values. Figure 8 shows a comparison between the simulated and AR&R IFD curves for a range of durations. The observed 24 hour IFD curve was also calculated using the daily data.

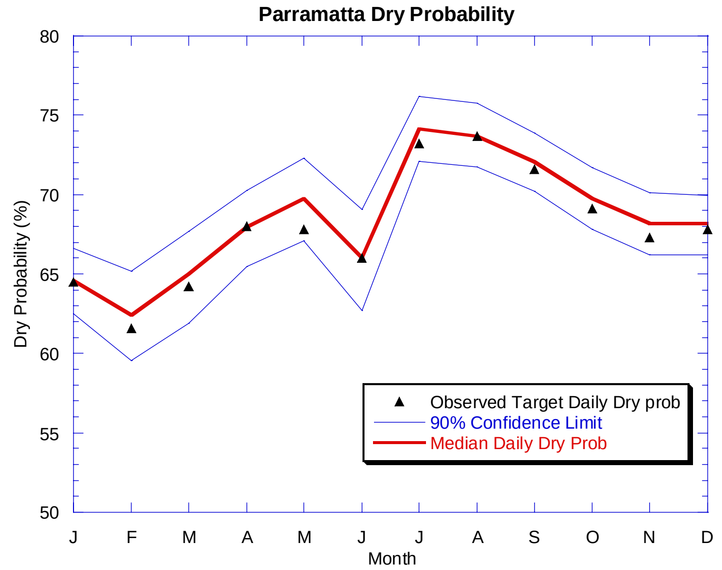


Figure 7. Parramatta observed vs simulated probability of a dry day.

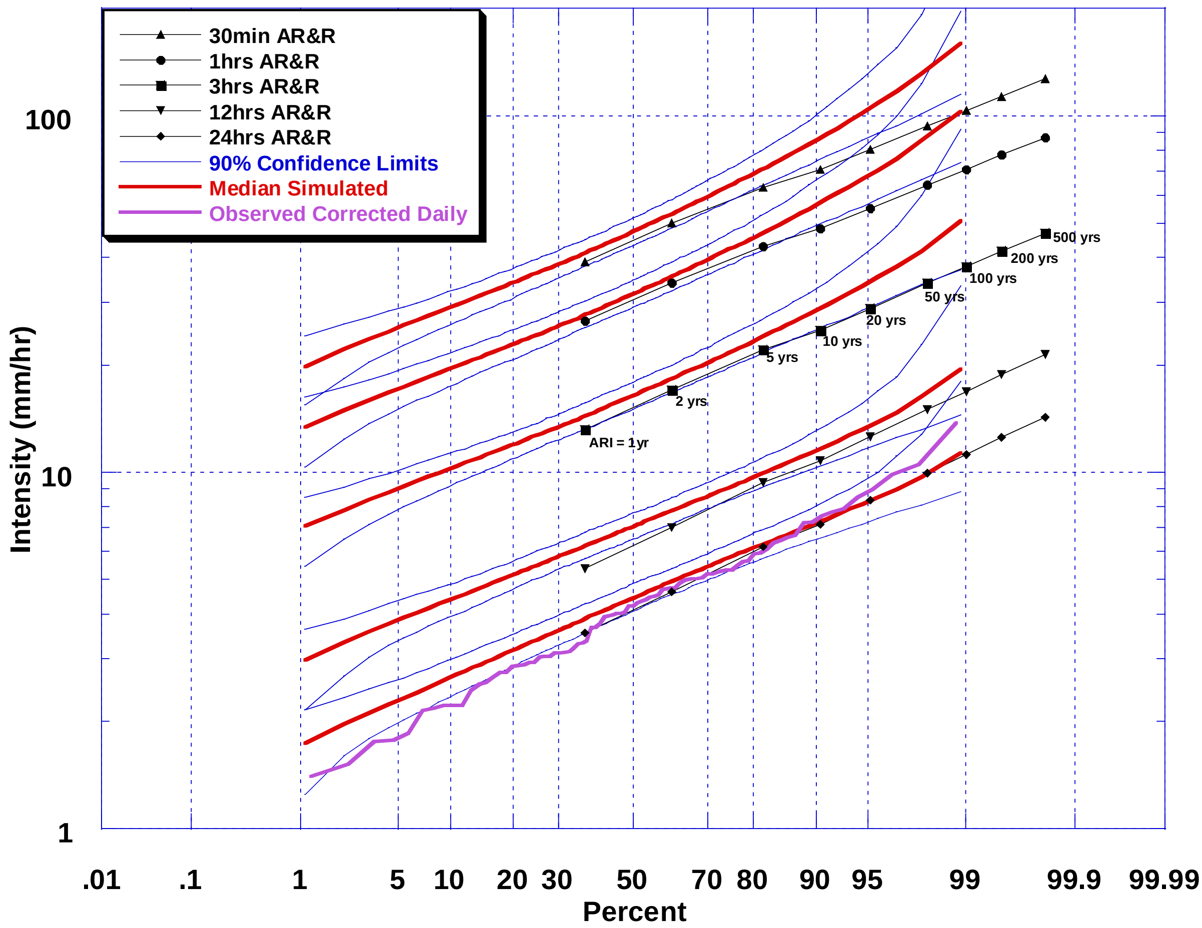


Figure 8. Parramatta observed vs simulated vs AR&R IFD curves.

The AR&R and observed 24-hour IFD curves show good agreement. It is noted that the observed IFD produces higher extreme intensities than does the AR&R curve. However, these differences are judged not be significant. Good agreement between the observed and the upper half of the DRIP 24-hour IFD curve is noted. DRIP overestimates the 24-hour intensities for more frequent events with an Average Recurrence Interval (ARI) less than 2 years with the observed curve lying just below the lower 90% confidence limit.

For durations less than 24 hours there are no adequate pluviograph data to check the DRIP IFD curves. As the ARI increases beyond 2 years the DRIP IFD curves consistently produce higher intensities than do the AR&R curves. For example the 100-year 30-minute intensity predicted by AR&R is 100mm/hr whereas DRIP predicts 150mm/hr. It is difficult to ascertain which is closer to the truth. However, three points deserve to be made:

1. For durations less than 12 hours, the DRIP IFD curves closely matched the data from Observatory Hill Sydney. It is stressed that DRIP is not calibrated to IFD data but rather individual storm event data. This engenders confidence in DRIP's ability to simulate extreme rainfall sequences.

2. The AR&R maps for 2 and 50-year short duration intensities are based on limited pluviograph data and reflect the exercise of judgement by experienced hydrometeorolgists. Bias in such circumstances is inevitable.

3. The DRIP IFD curves show weak positive skew for Parramatta, whereas the AR&R curves assume zero skew. At high ARI's such differences in skew exacerbate differences. Interestingly the DRIP 24-hour IFD shows virtually zero skew which is consistent with the 24-hour data. However, at smaller timescales, DRIP simulates skewed IFD curves. The AR&R procedure for deriving IFD curves assumes that one skewness applies to all durations. This assumption may have been necessary at the time of publishing the AR&R maps because of limited pluviograph data. However, such expediency does not assure the assumption is correct.

2.5 DRIP Calibration to Ryde Pumping Station Pluviograph

In view of doubt about the representativeness of the master site at Observatory Hill Sydney, it was decided to directly calibrate DRIP to a medium length pluviograph record considered to be more representative of the Parramatta site. In the search for a suitable site UPRCT provided the list of pluviograph sites, presented in Table 1, located within 10 km of Toongabbie, the centre point of the UPR catchment. 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 UPR catchment 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.

2.5.1 Calibration and Validation

The DRIP model was calibrated to the 53 years of pluviograph data available at Ryde pumping station. This gauge is operated by Sydney Water. The data was provided by

Australian Water Technologies. Several validation plots for DRIP simulation at the master site are shown below in Figures 9 to 11.

Table 1. List of pluviograph located within 10 km of Toongabbie.

Station	Pluviograph Name	Years of record as at Oct 20'00
566037	Ryde WPS	52.0
567079	Guildford (Pipehead)	29.3
566036	Potts Hill Reservoir	18.7
567092	South Prospect	17.7
567076	Castle Hill Stp	17.0
567104	Northmead Bowling Club	10.5
567111	Westmead Hospital	10.2
566081	Carlingford Bowling Club	10.0
567112	North Parramatta (Burnside Homes)	10.0
567147	Baulkham Hills Swimming Pool	10.0
567148	Kings Langley (Nsw Soccer Federation)	10.0
567151	Toongabbie Bowling Club	10.0
566086	Parramatta (Masonic Club)	9.9
567106	Rouse Hill (Api Country Club Kellyville)	9.9
566084	Quakers Hill Stp	9.9
567084	Quakers Hill Stp	9.8
567113	Blacktown (Ashlar Golf Club)	9.8
567146	Greystanes (Cumberland Golf Club)	9.7
567149	Cumberland State Forest (Ibm)	9.7
567150	Blacktown (Dog Pound)	9.7
567152	Merrylands West (Canal Road)	9.4
567153	Minchinbury (Pinegrove Memorial Park)	9.1
567162	Lalor Park (Vardys Rd)	7.8
567083	Prospect Reservoir	7.7
567167	Schofields (Fyfe Rd)	7.2
567075	Blacktown Survey Depot	3.6
567097	Kellyville Stp	2.2

Figure 9 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, Figure 10 shows that short timescale aggregation statistics such as daily and hourly means and standard deviation are satisfactorily reproduced by the DRIP simulation. Figure 11 shows that the probability of observing a dry hour or day is matched closely by simulated values.

Although the simulated aggregation statistics match the observed values well, extreme rainfalls on timescales from around 15 minutes to 6 hours are of most importance to this study. Therefore, the simulated IFD curves for a range of durations were compared to those observed in Figure 12.

For the durations shown, simulated IFD curves from 30 min to 3 hours match the observed values well. For durations greater than 12 hours, the simulated median values underestimate those observed for long recurrence interval periods. Nonetheless the observed IFDs lie within the simulation 90% confidence limits suggesting that sampling variability can account for the observed discrepancies. It is stressed that DRIP is not calibrated to IFD data but rather individual storm event data. This engenders confidence in DRIP's ability to simulate extreme rainfall sequences.

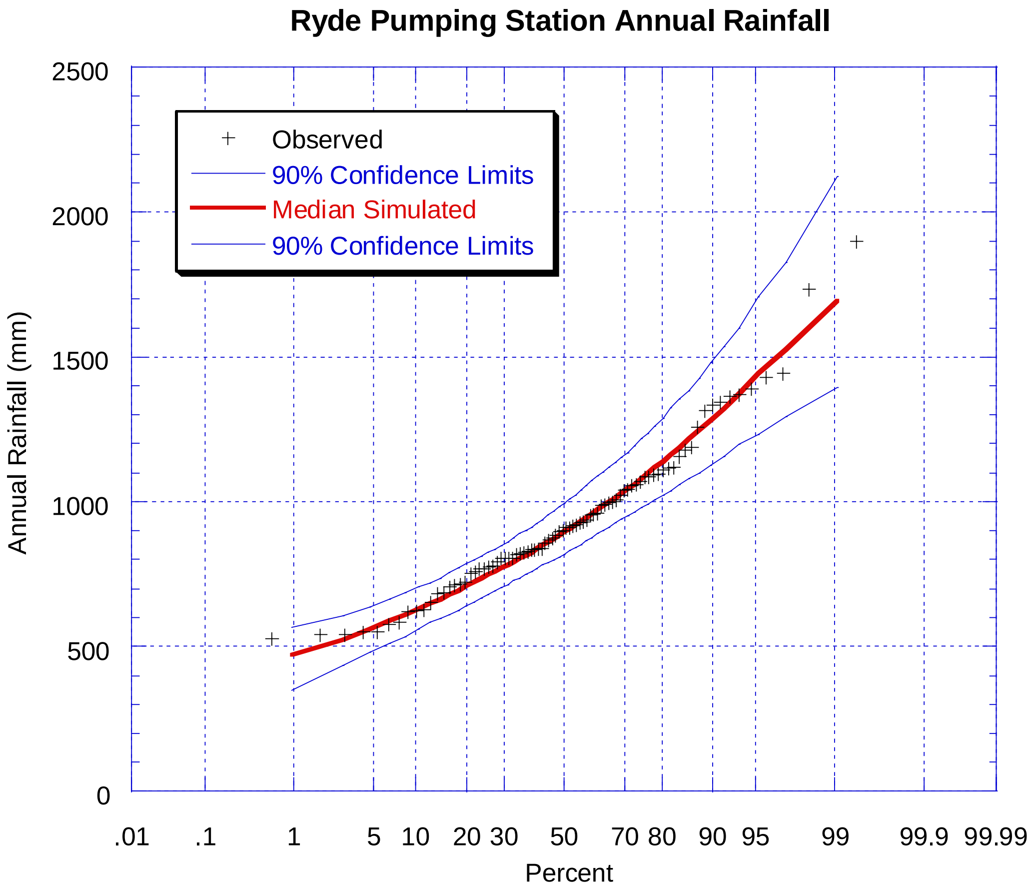
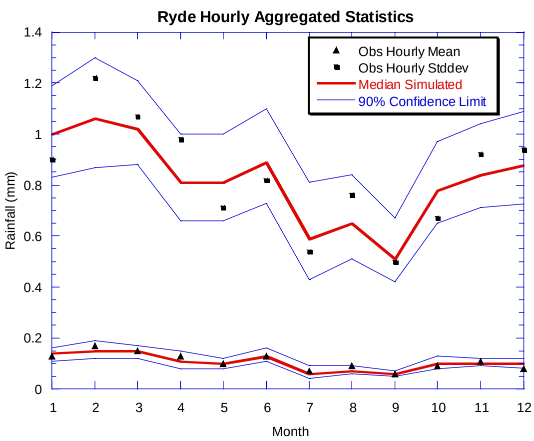


Figure 9. Ryde observed annual rainfall versus DRIP Simulation



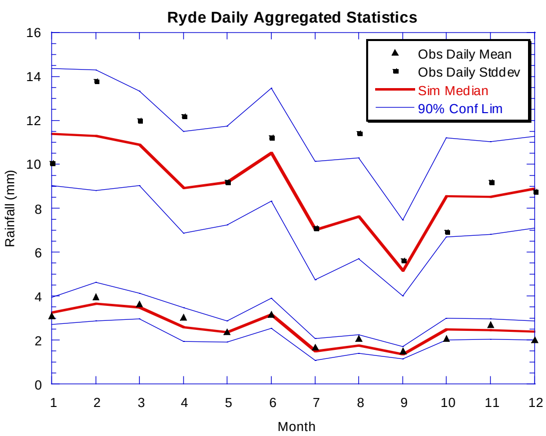


Figure 10. Ryde observed versus simulated (a) hourly and (b) daily mean and standard deviation of rainfall.