The Institution of Engineers, Australia
28th International Hydrology and Water Resources Symposium
10 -14 November 2003
Wollongong, NSW

Development of Stochastic Multisite Rainfall and Urban Water Demand for the Central Coast Region of New South Wales

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Abstract:

A novel approach for concurrently simulating daily catchment rainfall, streamflow and urban demand for water supply headworks modelling of the Central Coast Region of New South Wales is presented. A methodology for simulating daily multi-site rainfall based on rainfall at a single site generated using the DRIP (Disaggregated Rectangular Intensity Pulse) rainfall model by Heneker et al. [2000] was developed. This approach satisfactorily reproduces observed daily, monthly, annual rainfall statistics at the multiple sites. This demonstrates it is able to capture the inter-annual persistence and spatial variability that exists within the Central Coast water supply catchments. Rainfall series generated by the multi-site method are used in a non-parametric regional water demand model that incorporates water balances in households to estimate daily water demand in the Central Coast region of New South Wales. No metering data was available for this study other than daily water demand at the water treatment plants. Nonetheless the regional demand method was able to adequately estimate regional water demand including the day to day variation and strong seasonal trends of water demand in the Central Coast region.

Keywords: Synthetic rainfall, multi-site, urban water demand, headworks security, socio-economics

1. INTRODUCTION

The Central Coast region of New South Wales includes the Gosford and Wyong local government areas. The region is situated between the Sydney and Lower Hunter regions with the city of Gosford adjacent to the Sydney region and Wyong Shire extends to Lake Macquarie in the North. The Gosford-Wyong Councils' Water Authority (GWCWA) supplies water to the Central Coast region. In the year 2002 the region had an estimated population of 300,400 people with a growth rate of 1.37% per annum that is expected to slow to 0.24% per annum in 2030.

The region's water supply headworks system presently includes a major surface reservoir on Mangrove Creek with additional water harvested downstream from Mangrove Creek's residual catchment, Mooney Mooney Creek, Ourimbah Creek and Wyong River catchments. Mangrove and Mooney Mooney Creeks discharge to the Hawkesbury River. Ourimbah Creek and Wyong River discharge to Tuggerah Lakes.

GWCWA are evaluating the ecological significance of stream flows in their water supply catchments and the impact of water supply and demand management measures in urban areas. In order to evaluate the impact of water extractions on the ecology of streams daily water demand and headworks models were required.

Many authors including Maidment et al. [1985], Kuczera and Ng [1994], Zhou et al. [2000] and Coombes et al. [2000; 2002] have established that urban water demand is dependent on seasonal and climatic variables. To accurately determine the impact of urban water demand on streamflow the correlation between climatic conditions, domestic water use and streamflow must be maintained. In particular the correlation between hot dry conditions, high domestic water use and low stream flow and vice versa must be preserved because it is likely to have significant impact on the viability of streams and the reliability of water supply headworks systems.

The spatial variance of urban water demand is often ignored in analysis of water supply headworks systems in preference to the use of total regional demand. Maidment and Miaou [1986] established that water use in different locations was dependent on spatially averaged rainfall series, ambient air temperatures and established water use patterns. Coombes et al. [2000; 2002] found that urban water demand was spatially dependent on local climatic and socio-economic variables. The use of demand and supply management measures such as rainwater tanks and AAA shower roses was expected to further increase the spatial and day to day variation of water demand.

A modified version of the network linear program for headworks simulation WATHNET by Kuczera [1992] was employed to analyse stream flows and headworks security. To preserve the climatic correlation between the urban and water supply catchments the DRIP synthetic rainfall model by Heneker et al. [2001] was used in a multi-site framework to generate daily rainfall series. The rainfall series was used at each time step in the headworks model to determine stream flow using a rainfall/runoff model and urban water demand using the non-parametric regional demand method by Coombes et al. [2002].

The formulation of a multi-site synthetic rainfall model and the subsequent generation of urban water demand are discussed in this paper.

2. MULTI-SITE DAILY RAINFALL GENERATION

In this study a new approach was developed to generate multi-site daily rainfall data within the GWCWA's water supply catchments. The approach is described as follows: The DRIP model was used to generate daily rainfall at a single primary site and then a transfer scheme was applied to simulate daily rainfall at several other sites conditioned on the rainfall at the primary site. The DRIP model was chosen because it is an event based rainfall model which can reproduce inter-annual persistence evident in rainfall data from sites such as Sydney (Frost et al, 2000). There is strong evidence of an inter-annual persistence similar to the Sydney data in the rainfall data within the Gosford-Wyong water supply catchment (Thyer and Kuczera, 2003).

Recent research has investigated the regionalisation of the DRIP model so that it can be used to simulate rainfall at sites where only daily rainfall data are available for model calibration [Jennings, 2003]. This technique essentially scales the DRIP model parameters derived for a key site to reproduce the daily rainfall statistics at another target site. In this study the key site was the Sydney Observatory Hill gauge and the target site was the Gosford gauge. The length, accuracy and availability of rainfall data at the Observatory Hill gauge motivated its selection as a key site The DRIP model was able to adequately reproduce the daily rainfall statistics (mean, standard deviation, probability of a dry day) for the majority of months and the annual rainfall distribution for Gosford site (Figure 1).

2.1 Multi-site Daily Rainfall Transfer Scheme

To provide a suitable representation of the rainfall regime within GWCWA's water supply catchment simulation of daily rainfall at three other sites was required. These sites included another coastal site at Wyong and two sites situated further inland at Kulnura North and Mogo Creek. A methodology was required to transfer the DRIP simulated daily rainfall at Gosford to the three other sites.

A stepwise approach was adopted where at each step daily rainfall at one secondary site was simulated conditional on rainfall data from a number of other primary sites. Therefore, at the first step Wyong rainfall was based on the Gosford rainfall, in the second step Kulnura North rainfall was conditional on Gosford and Wyong rainfall and in the third step Mogo Creek rainfall was based on the rainfall from the other three sites.

Each step in this procedure had two stages. In the first stage the secondary site daily rainfall occurrence is simulated using the following conditional probability:

$$P\left(R_s \middle| \left\{S_p^i, i = 1, N_p\right\}\right) \tag{1}$$

where R_s is the rainfall occurrence (wet or dry) at the secondary site and S^i_p is the daily rainfall state of primary site I = 1, …, N_p primary sites.

The daily rainfall state at each of the primary sites was based on daily rainfall depth. This approach was used because it was found that the conditional occurrence probability was strongly dependent on the rainfall depth at the primary site(s). Five daily rainfall states and their rainfall ranges were arbitrarily chosen. The simulation results given in the following section show that this approach was able to satisfactorily reproduce the observed daily rainfall occurrence probabilities at each of the secondary sites. The scheme summarized in (1) exploited the observation that there was a low probability (<4%) of rainfall at the two inland sites if there was no rainfall at either of the two coastal sites.

Table 1: Daily Rainfall States

Daily Rainfall State, S	Daily rainfall depth, y
1	$y = 0$
2	$0 < y \leq 5$
3	$5 < y \leq 20$
4	$20 < y \leq 50$
5	$y > 50$

In the second stage the secondary site daily rainfall depth was simulated using the following approach: If there was a strong correlation between the secondary and primary site's daily rainfall then a regression of inverse normal transformed amounts was used to simulate secondary site daily rainfall. The details of this daily rainfall depth regression model are given by Charles et al. [1999].

An inverse normal transformation was used on the daily rainfall depths because it produced residuals which did not strongly violate the assumption in the regression model that the errors are normally distributed. Two sets of regression parameters, one for the summer (Nov. to Apr.) and one for the winter (May to Oct.) were required to capture the seasonal differences in spatial rainfall variability due to the different weather patterns that produce rainfall in each season. If there was no rainfall at any of the primary sites or the daily rainfall correlation between the secondary and primary sites was low then the secondary site rainfall was sampled from its observed historical distribution for the particular primary site rainfall occurrence pattern.

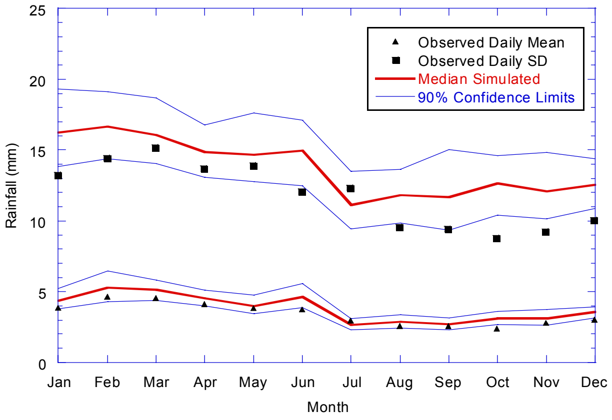
2.2 Multi-Site Daily Rainfall Simulation Results

To evaluate the performance of the approach outlined above 1000 simulations of daily rainfall time series with the same length as the historical record were generated for each site. If the observed values of the relevant statistics were within the 90% confidence limits calculated from these multiple simulations then the model is considered to be not inconsistent with the observed values.

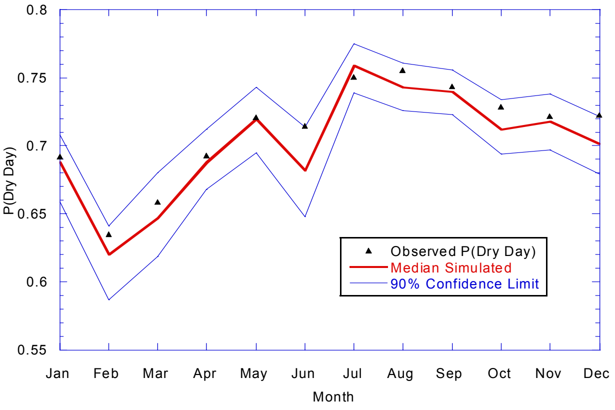
In this study the relevant statistics compared were the daily and monthly mean and standard deviation (SD), probability of a dry day, the annual distribution and monthly and annual correlations. A full analysis of these results is presented in Thyer and Kozarovski [2001].

For all four sites the observed daily means were within the simulated 90% confidence limits for a majority of months. The results for the simulated daily SD's were reasonable, although not as good as the daily means. This is likely because the results for the three other stations are based on the rainfall simulated at Gosford. Therefore any deficiencies in the rainfall simulated at Gosford will also be evident at the other sites. Figure 1 and Figure 2 shows the results for Gosford and Mogo Creek respectively.

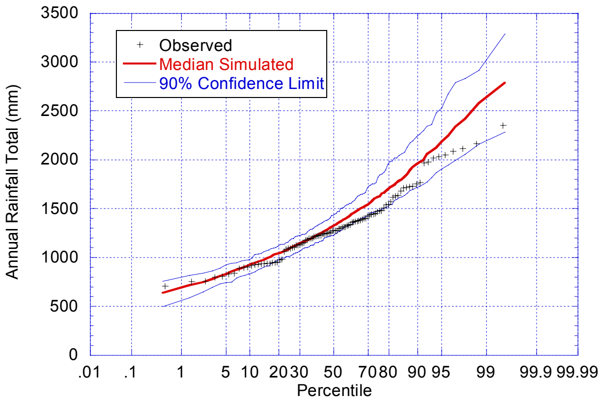
The observed dry day probabilities were within the simulated 90% confidence limits for Gosford and Wyong for all months. For Kulnura North and Mogo Creek there are some months where the observed values fall just outside the simulated confidence limits. Similarly for the monthly means and SD's the observed values for Gosford and Wyong were well reproduced, while for Kulnura North and particularly Mogo Creek the number of months outside the 90% confidence limits was higher. However, overall the results were considered to be reasonably good.



(a) Daily Mean and SD



(b) Dry Day Probability

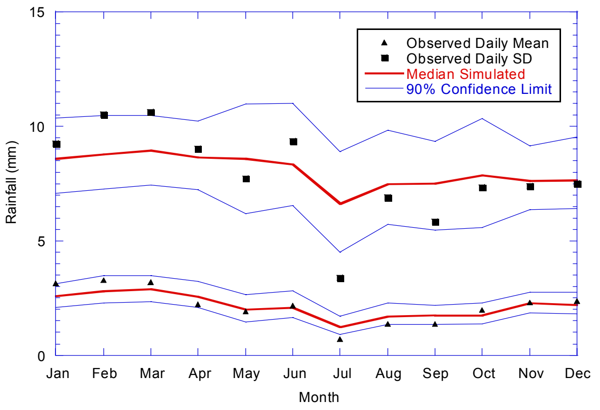


(c) Annual Distribution

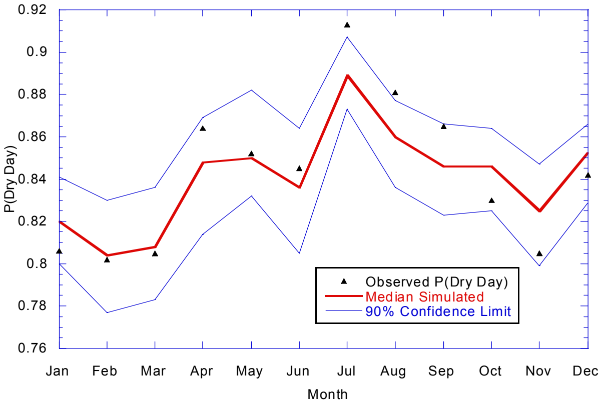
Figure 1 – Comparison of observed and simulated statistics for Gosford.

At all four sites a majority of the observed annual distribution was within the simulated 90% confidence limits. Figure 1(c) shows these results for Gosford. The results for Mogo Creek show that the upper tail of the distribution seems to be underestimated [Figure 2 (c)]. This is likely because the DRIP model was calibrated to Gosford rainfall from a long record covering 1886-1992, whereas the observed record for Kulnura North was from a more recent and comparatively wetter period, 1963-

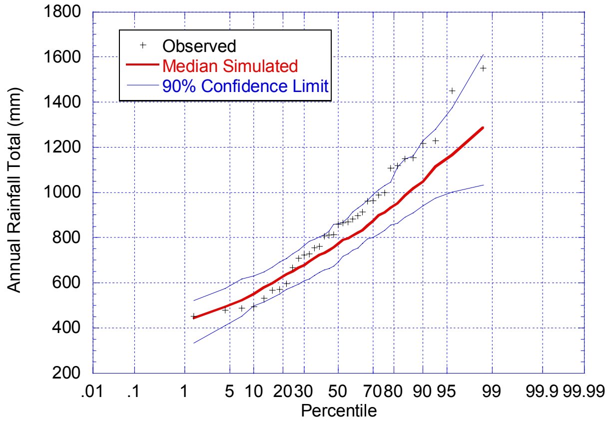
1992. Hence, as these simulated values are based on a longer time series, they may provide a better representation of the long-term rainfall characteristics.



(a) Daily Mean and SD



(b) Dry Day Probability



(c) Annual Distribution

Figure 2: Comparison of observed and simulated statistics for Mogo Creek.

For the monthly and annual inter-site correlations the simulated values are generally below the observed values. This highlights a possible deficiency in the approach. One of the assumptions was that the daily rainfall occurrence probability was independent of the previous day's rainfall. If the probability given in (1) was conditioned on the previous day's rainfall then improved results for the inter-site correlations may be possible.

The results show that the daily rainfall transfer scheme was able to adequately reproduce the majority of relevant statistics from the daily, monthly and annual time scales for all four rainfall sites. The results for the two coastal sites at Gosford and Wyong were better than the results for the inland sites at Kulnura North and Mogo Creek. Given the challenge of simulating daily rainfall at multiple sites based on the rainfall at a single site in a different climate zone this is considered to be an excellent result.

It is reiterated that one of the major advantages of this approach is that the simulated time series can reproduce the inter-annual persistence and spatial variability that is evident in the Central Coast region. For water resource planners this greatly improves the confidence in simulated drought risks. In addition, using a stochastic approach eliminated the need to infill any missing data which can reduce the spatial variability in daily rainfall. Instead, has a mechanism which exploits the spatial variability in GWCWA's water supply catchment. This methodology represents a significant improvement in the previous efforts to simulate hydrological time series for this catchment.

3. ESTIMATION OF WATER DEMAND

A method was required to simulate regional water demand in the Gosford and Wyong local government areas using synthetically generated daily rainfall data and observations of regional daily demand taken at the water treatment plant.

3.1 Estimating Household Water Demand

GWCWA does not have a monitoring program that disaggregates household water use into indoor and outdoor components. Indeed distributed monitoring or metering data for urban water demand was not available for this study. Accordingly, methods were developed to transfer results from the Lower Hunter region to the Central Coast region that were verified using daily bulk water use measured at the water treatment plants and the proportion of domestic household water use (64%) estimated from billing records.

A set of methods to estimate domestic water demand have been developed by Coombes et al. [2000] using monitoring data from the Lower Hunter region of New South Wales. These methods are based on data from 130 households monitored for indoor and outdoor water use in different socio-economic zones over a 12 year period.

A linear regression was developed to estimate daily household water use in the Lower Hunter zones using climate, socio-economic and water use data. The long-term average daily indoor water use for a particular month (inDem) in L/day was estimated using:

$$\begin{aligned} \text{inDem} &= 27.79 + 145.69\ \text{P} - 0.422\ \text{M} - 10.579\ \text{AveR} \\ &\quad + 6.74\ \text{AveRdays} - 0.162\ \text{Inc} - 12.28\ \text{G} \\ &\quad + 0.49\ \text{AveTemp} \qquad (1) \end{aligned}$$

where P is the number of occupants in a dwelling, M is a seasonal index ranging from 1 to 6 (the index for January and December is 1, and the index for June and July is 6), Inc is average weekly income per person ($), G is annual population growth (%), and for the month in question, AveR is long-term average daily rainfall (mm), AveRdays is the long-term average number of days with rainfall and AveTemp is the long-term average daily maximum temperature (°C).

Equation (1) yielded a coefficient of determination (R^2) of 0.81. The long-term average daily outdoor water use for a particular month (exDayDem) in L/day was estimated using:

$$\begin{aligned} \text{exDayDem} &= -251.5 + 7.53\text{M} - 11.3\text{AveR} \\ &\quad - 0.025\,\text{Inc} - 0.816\ \text{AveRdays} \\ &\quad + 24.44\text{G} + 19.08\,\text{AveTemp} \qquad (2) \end{aligned}$$

Equation (2) yielded an R^2 value of 0.69. These equations show that indoor and outdoor water use from the Lower Hunter region was is strongly dependent on the climatic and demographic variables [Coombes et al., 2000]. Monthly daily average domestic water demand for different dwelling types within the Gosford and Wyong zones was estimated using climate and socio-economic data from the Australian Bureau of Statistics [ABS, 2000] (shown in Table 2) in Equations (1) and (2).

Table 2: Climatic and socio-economic data for the Central Coast region

Zone	**Gosford**	**Wyong**
Average weekly income ($/person)	293	251
Average daily rainfall (mm/day)	3.67	3.33
Population growth rate (%/year)	1.84	2.35
Average maximum daily temperature (°C)	22.9	24.1
Average rain days per month (days)	12	10

The estimated monthly average daily indoor and outdoor water demand for the Gosford and Wyong areas for different household sizes is shown in Tables 3 and 4 respectively. The monthly average daily water use results shown in Tables 3 and 4 were used in the PURRS model by Coombes and Kuczera [2001] in combination with historical climate data to create resource files of domestic water demand in a variety of dwelling types for use in the regional demand model. The dwelling types used in the study are shown in Table 5.

Table 3. Estimated average daily household water use for the Gosford area

	Average water use (Litres per day)					
	Outdoor	**Indoor (number of occupants)**				
Month		**1**	**2**	**3**	**4**	**5+**
January	271	151	296	442	588	734
February	254	140	286	431	577	723
March	232	147	292	438	584	730
April	207	141	287	432	578	724
May	162	137	283	428	574	720
June	119	133	279	424	570	716
July	121	137	282	428	574	719
August	173	143	289	434	580	726
September	224	144	290	435	581	727
October	272	148	294	440	586	731
November	292	151	296	442	588	733
December	331	152	297	443	589	734

Table 4. Estimated average daily household water use for the Wyong area

	Average water use (Litres per day)					
	Outdoor	**Indoor (number of occupants)**				
Month		**1**	**2**	**3**	**4**	**5+**
January	317	165	311	456	602	748
February	302	152	297	443	589	735
March	285	163	309	454	600	746
April	256	153	299	444	590	736
May	188	156	302	447	593	739
June	136	143	289	434	580	726
July	157	150	296	442	587	733
August	197	152	298	443	589	735
September	252	154	300	446	592	737
October	309	162	308	453	599	745
November	344	161	307	453	598	744
December	392	159	305	450	596	742

3.2 Compiling Regional Urban Water Demand

The Central Coast region was divided into two zones with different climatic conditions (rainfall, temperature and number of days since last rain day): namely Gosford and Wyong.

A method of non-parametric aggregation was used to generate daily domestic water use for each dwelling type in each climate zone using the historical resource files. The daily water balance results from the PURRS model was compiled into daily water use totals and combined with the historical daily climate data (rain depth, number of days since last rain day and maximum ambient air temperature) to create resource files of water demand. If there are N_R years of daily climate data, the resource file has N_R replicates for each day of the year.

Table 5 Dwelling types

Item	Occupants	Dwellings
H1	1	1
H2	2	1
H3	3	1
H4	4	1
H5	5+	1
C1	11	4
C2	24	9

In the headworks modelling let $AveTemp_m^H$ be the daily maximum temperature (ºC), $Rdepth_m^H$ be the daily rainfall depth (mm) and $DryDays_m^H$ be the number of days since last rain event for day m for each zone used in the regional demand model. The climate variables in the headworks model were derived using the synthetic rainfall series generated by the DRIP model. Importantly they are temporally and spatially consistent with the rainfall and stream flows in the water supply catchments.

The difference between climate data used in the headworks simulation and the resource file $Diff_m^j$ for replicate j of day m in the resource file for a particular demand zone is shown as follows:

$$\begin{aligned} Diff_m^j &= w_1 \mid AveTemp_m^H - AveTemp_m^{R,j} \mid \\ &+ w_2 \mid DryDays_m^H - DryDays_m^{R,j} \mid \\ &+ w_3 \mid Rdepth_m^H - Rdepth_m^{R,j} \mid \qquad (2) \end{aligned}$$

where w_1, w_2 and w_3 are weights, which were set to 1 in this study.

The dwelling statistics from the Central Coast region used in this study are shown in Table 6.

Table 6: Dwelling statistics for the Central Coast region

Item		**Wyong**	**Gosford**
Houses (%)		85.8	85.8
Units (%)		14.2	14.2
Occupants per dwelling by area population (%)	**1**	25	23.9
	2	35	34.3
	3	15	15.2
	4	15	16
	5+	10	10.6

For each day m in each zone the index j in the resource file which minimizes $Diff_m^j$ is identified and the corresponding values for water use for cluster C1 (C1W and C1T), cluster C2 (C2W and C2T), house H1 (H1W and H1T), house H2 (H2W and H2T), house H3 (H3W and H3T), house H4 (H4W and H4T) and house H5 (H5W and H5T) are selected from the resource file. The domestic demand Dem_m^i (ML) for record m in zone i is:

$$\begin{aligned} Dem_m^i &= (1 - inst_m).Pop_m \cdot \begin{pmatrix} F_1C1W + F_2C2W \\ + F_3H1W + F_4H2W \\ + F_5H3 + F_6H4W \\ + F_7H5W \end{pmatrix} \\ &+ (inst_m).Pop_m \cdot \begin{pmatrix} F_1C1T + F_2C2T \\ + F_3H1T + F_4H2T \\ + F_5H3T + F_6H4T \\ + F_7H5T \end{pmatrix} \qquad (3) \end{aligned}$$

where the factors F_1 to F_7 indicate the proportion of the population (Pop_m) in a zone that occupies a particular dwelling type derived from the data shown in Table 6 and the installation fraction for rainwater tanks or demand management measures is $inst_m$.

Population data used in this study was provided by the Australian Bureau of Statistics [ABS, 2000], Planning NSW and Wyong City Council and is shown in Table 7.

Table 7: Population statistics

	Number of people	
Year	**Gosford**	**Wyong**
1996	150,220	120,185
1997	153,024	123,108
1998	154,946	125,946
1999	158,172	129,309
2001	159,412	134,424

The total regional domestic demand $DomDem_m$ (ML) on day m is:

$$DomDem_m = \begin{cases} \sum_{i=1}^{n} Dem_m^i & \text{If Month} \neq \text{Dec, Jan or Feb} \\ Hol \sum_{i=1}^{n} Dem_m^i & \text{If Month = Jan} \\ Hol1 \sum_{i=1}^{n} Dem_m^i & \text{If Month = Dec or Feb} \end{cases} \qquad (4)$$

$$DomDem_m = \begin{cases} WE.DomDem_m & \text{If Day = Sat or Sun} \\ DomDem_m & \text{Otherwise} \end{cases} \qquad (5)$$

where n is the number of zones in the region Hol and Hol1 are multipliers of water demand during summer holiday periods and WE is a multiplier of water demand during week ends. A daily outdoor multiplier Ex is also used in the calibration.

Non-domestic monthly demand for a region also needs to be accounted for. The simple model of commercial and industrial water use developed by Kuczera and Ng [1994] was altered to produce a model of daily non-domestic demand defined as follows:

$$Q_{IC} = \left[A + B(Year - yr)\right] \left\{1.0 + Amp * Sin\left[\frac{2\pi}{12}(mth + Phase)\right]\right\}^{Pow} - C * Rd + D(T - T_{ave})Rcount \quad (6)$$

$$Q_{iC} = \begin{cases} Hol.Q_{IC} & \text{If Mth = Jan} \\ Hol1.Q_{IC} & \text{If Mth = Dec or Feb} \\ Q_{IC} & \text{Otherwise} \end{cases} \quad (7)$$

where Q_{IC} is the non-domestic demand for month mth and year Year, A and B are parameters defining the long-term trend in consumption, Amp and Phase are parameters defining the seasonal cycle, Pow is an exponant used to control the magnitude of demand, C is a parameter accounting for the effect of daily rain depth Rd, T is the daily maximum temperature, T_{ave} is the long term daily average daily maximum temperature and Rcount is the count of days since the last day with rainfall.

Because no metered domestic data was available the non domestic water use model had to be calibrated to the difference between household and total consumption and accounts for about 36% of total mains water use for the Central Coast region including unaccounted-for consumption and losses. The regional demand model implements equations (2) to (7) to produce total domestic and non-domestic demand for the Central Coast region.

4. RESULTS

Calibration of the regional demand model to daily demand data recorded at the central water treatment plants during the period April 1996 to December 2001 provided a reasonable agreement to observed demand with an R^2 value of 0.55 and a SD of ±15.5 ML/day.

The regional demand model was able to reproduce the strong seasonal variation in water demand experienced in the Central Coast region (Figure 3). The monthly and annual water use volumes were also accurately reproduced (R^2 = 0.78 and 0.92 respectively). Figures 3 and 4 show that the model was able to estimate summer peak demands and the day to day variation in water demand but in Figure 4 it is shown the model could not fully describe the variation in summer water demand. However given that domestic, commercial and industrial metering data was not available for this study the regional demand model has provided an acceptable estimation of regional water demand.

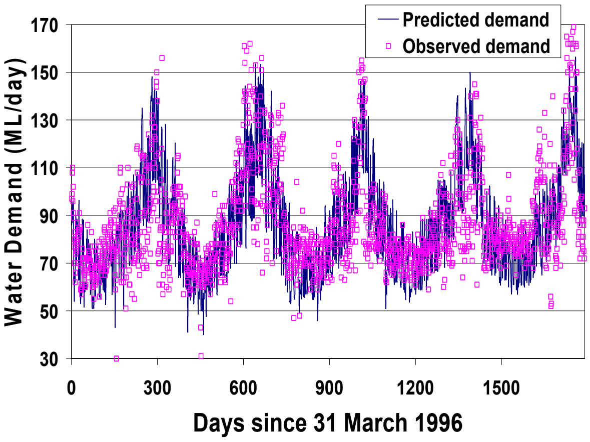


Figure 3: Calibration of the regional demand model to observed data

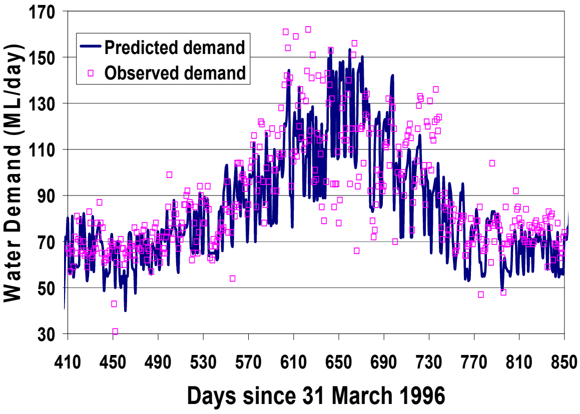


Figure 4: Comparison between observed and predicted data for the summer of 1998

Water demand in the Central Coast region was found to be strongly dependent on the climatic variables daily rain depth, days since last rain event and daily maximum temperature. A selection of model parameter values used to calibrate the regional demand model are shown in Tables 8.

Table 8: Model parameters

WE	Ex	Hol	Hol1
1.1	0.21	1.3	1.1

Table 8 shows that domestic water demand increased by about 10% on weekends (WE). During the peak holiday period in January regional water demand was estimated to increase by 30% (Hol). In December and February the holiday period was estimated to increase regional water demand by 10% (Hol1). The result for the outdoor water use multiplier (Ex) of 0.21 is of interest. This indicates that peak outdoor water demands at each dwelling in the region do not occur simultaneously.

Indeed the results indicate that only 21% of domestic dwellings contributed to the peak water demand on any day. This result also suggests that not all domestic dwellings will simultaneously have no outdoor water use on a low demand day indicating that probabilistic behavioural distribution of outdoor water demand [see Coombes et al., 2000] will also need to account for natural variation across different scales.

5 CONCLUSIONS

This study describes the development of a multi-site synthetic rainfall series that was used to simultaneously estimate stream flow in water supply catchments and water demand in urban areas. Thus the method was able to maintain a correlation between stream flow in the water supply catchment and urban water demand. In particular the correlation between hot dry conditions, high domestic water use and low streamflow and vice versa is more likely to be preserved. The methodology will allow improved understanding of the security of water supply.

Multi-site production of synthetic daily rainfall using the DRIP model was able to simulate daily rainfall at multiple sites based on rainfall at a single site and reproduce the inter-annual persistence and spatial variability that exists within the Central Coast water supply catchments. The multi-site rainfall method described in this study has potential to significantly improve the simulation of hydrological time series in catchments. Nonetheless the method experienced some difficulty in reproducing statistics at the inland sites that may be improved with a different configuration of the multi-site daily rainfall conditioning scheme.

The multi-site rainfall series generated using DRIP was used to generate the climatic parameters daily rain depth, days since last rainfall event and maximum temperature that were employed in a regional demand method to produce daily water demand in the Central Coast region. No metering data was available for this study other than daily water demand at the water treatment plants. Nonetheless the regional demand method was able to adequately estimate regional water demand including the day to day variation and strong seasonal trends of water demand in the Central Coast region.

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