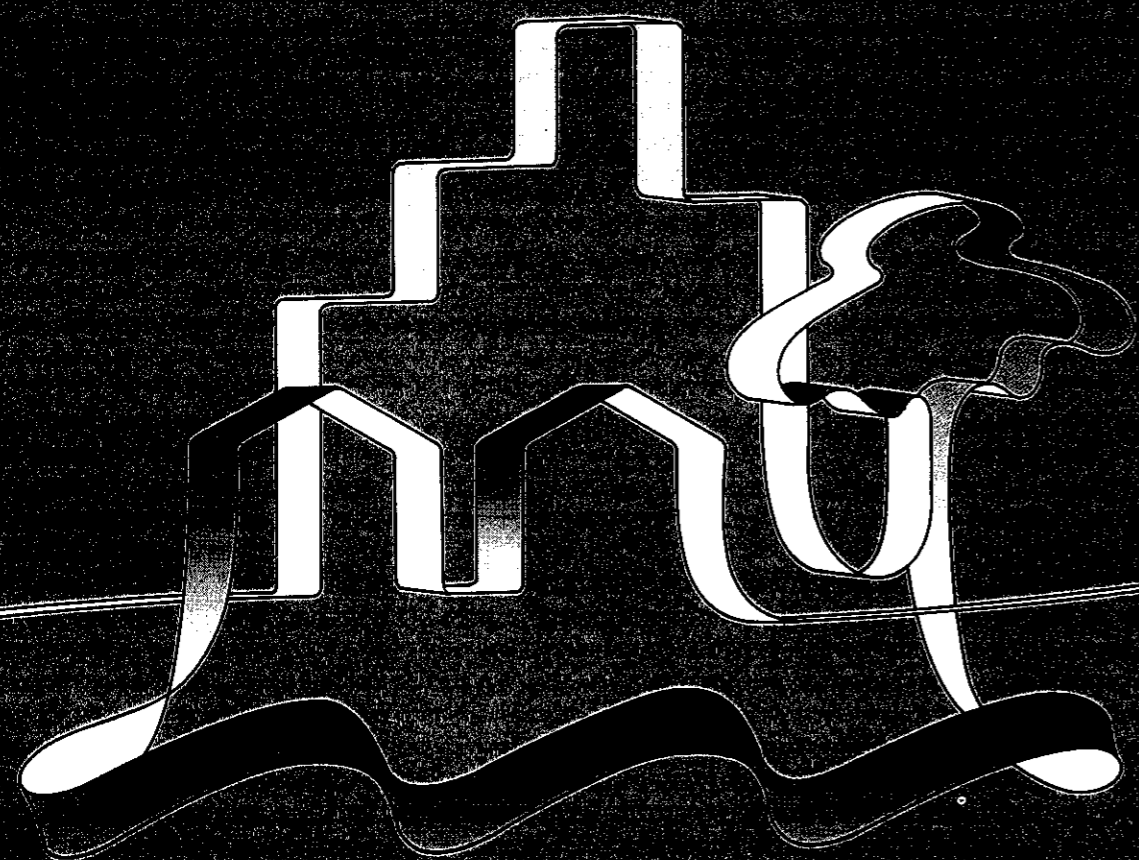




Urban Water Research Association of Australia

# Simultaneous Peak Water Demands in Residential Areas



Research Report No. 67

## URBAN WATER RESEARCH ASSOCIATION OF AUSTRALIA

The Association was formed in 1986 following initiatives by the Australian Water Research Advisory Council and the Major Urban Water Authorities of Australia. The Association's primary role is to foster and promote a comprehensive, co-ordinated and cost-effective approach to urban water research within Australia, for both metropolitan and non-metropolitan areas.

The Association invites proposals for research work through its member authorities and allocates funding to approved projects on an annual basis. The actual research is undertaken by water authorities, research organisations, universities, consultants and government agencies.

The UWRAA Research Report series presents information resulting from research projects supported by the Association and is published as a record of the work undertaken and as a means of disseminating the research findings. The Association also encourages the presentation of findings by the researchers in professional journals and at conferences. The Association's reports are indexed on STREAMLINE, the national water data base.

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## Urban Water Research Association of Australia

# Simultaneous Peak Water Demands in Residential Areas

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## FOREWORD

This report is based on UWRAA Research Project No WS-54: 'Simultaneous peak water demands in residential areas' which was undertaken during the period July 1991 - June 1993. Organisational responsibility for the project was as follows:

Sponsoring Authority	:	Water Authority of Western Australia
Project Officer	:	Mr John Janssen, Water Authority of Western Australia
Research Agencies	:	CSIRO Division of Water Resources Data Analysis Australia Pty Ltd
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The project was funded by the Urban Water Research Association of Australia and by the Water Authority of Western Australia.

## SUMMARY

Water distribution networks must have sufficient capacity to ensure that minimum head requirements at consumer supply offtakes are met during the peak demand period. To achieve this, the design of networks, using computer modelling, requires a clear understanding of the water usage patterns of consumers during this period.

Existing models used by the Water Authority of Western Australia have recognised that the peak water usages by individual consumer services occur at varying times, giving a diversity effect, but have assumed that the distribution of demand at each service can be described statistically as a normal distribution.

The aim of this study was to assess diversity effects during times of peak water use in the Perth summer and involved the recording of instantaneous water use by a sample of 84 Perth households continuously over a period of three months.

The major findings of the study are:

1. During the time of peak water usage (typically at around 6.30 pm on a day with high temperatures and easterly winds) a large proportion of households are still using little or no water.
2. Consequently the traditional models for water demand which assume a normal distribution are particularly inappropriate. There is a need for a skew distribution with an extended upper tail.
3. The Gamma distribution with a shape parameter around 0.2 to 0.3 provides a good model for the observed demand during peaks. The model is best in the upper tail, the region most critical in a description of the diversity effect.
4. No evidence was found for correlation of demand by nearby households. Pressure and long and short services also did not have a measurable effect on peak consumption. However the relatively small sample size (84 households) suggests that this should not be taken as conclusive evidence that correlation can always be ignored.
5. The effect of moving from normal distribution models to Gamma distribution models has a similar effect on the general shape of diversity curves to that of introducing correlation to the normal distribution model. Consequently it is likely that earlier studies which used normal distribution models may have interpreted distribution effects as correlation.

In addition the study developed methodologies for the optimal collection and analysis of instantaneous demand data.

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# 1. INTRODUCTION

The Water Authority of Western Australia currently allows for diversity effects in the design of water reticulation systems. The aim of this study was to gather information on instantaneous peak demand for water by domestic services in the Perth metropolitan area with a view to refining currently used diversity curves.

To appreciate the issues involved, it is necessary to briefly consider what diversity curves are and how they are used in the design of a water reticulation network.

## 1.1 Diversity

When considering a single service, it is usual to design the network (and in particular the pipe diameters) to provide a specified pressure while the service is drawing a specified flow. The specified flow is essentially the maximum reasonable demand. Such a design calculation is relatively easy. When considering several services close to each other on the network, it is possible to produce a very conservative design by assuming that all the services are drawing the same specified flow simultaneously. That is, the average demand at the peak is equal to the peak demand for a single service.

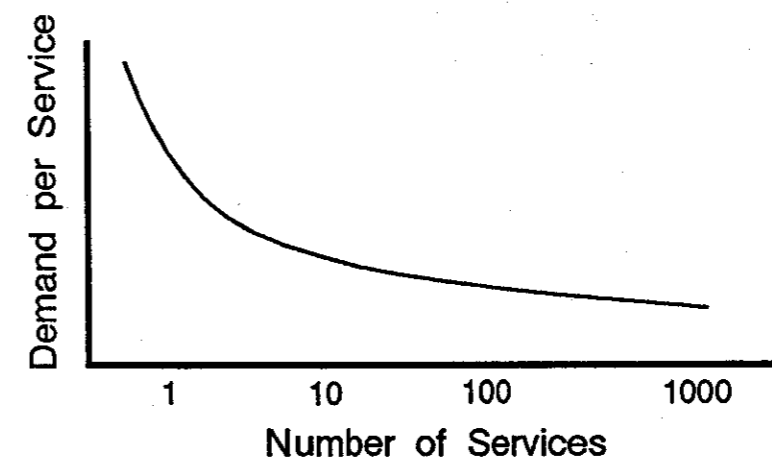


Figure 1.1 : A typical diversity curve.

This assumption is clearly unrealistic. In practice, it is extremely unlikely that all the services would be drawing their peak demand at the same time. Hence the maximum average demand for a group of services is likely to be significantly less than the maximum for a single service. When considering a very large number of services

it is sufficient to simply consider average flow at the time of system peak demand – maxima are no longer relevant. This leads to a curve as shown in Figure 1.1, with the maximum demand per service decreasing as an increasing number of services are considered. This is a diversity curve.

The form of the diversity curve depends upon:

- 1 the distribution of demand from a typical service;
- 2 how this demand varies over time; and
- 3 the simultaneous behaviour of adjacent services.

Various assumptions about these factors give differing parametric representations of diversity curves.

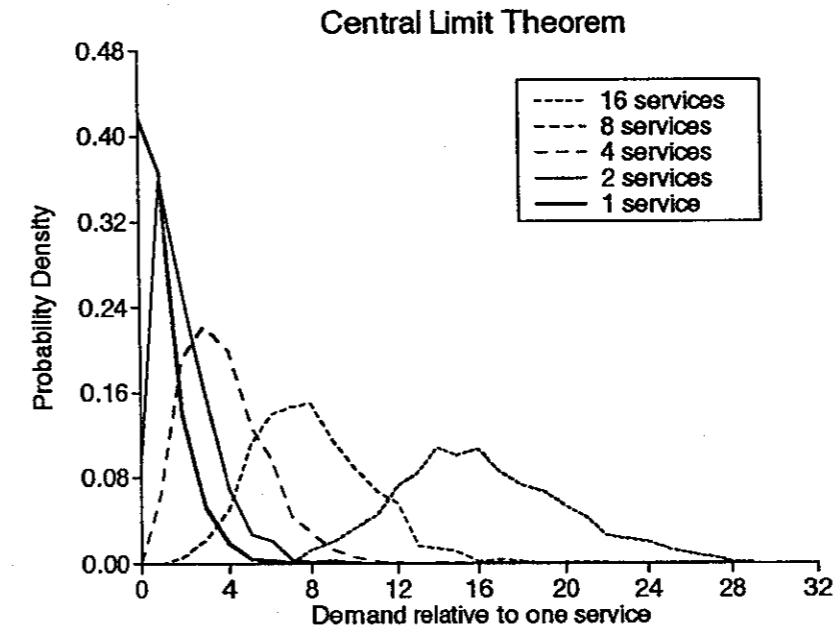
## 1.2 Distribution of demand

The variation in demand has two dimensions. The demand from a single service will vary over time and at a particular time there will be variation in demand between services. In studying diversity, it is the latter variation which is most critical (it is the very cause of diversity) but there is a question as to what times should be studied. For most purposes it is assumed that the only relevant time to consider is the instant of peak system demand, although it is likely that in any given area the peak will not coincide with the system peak.

The distribution of demand by a single service over time tends to be highly skewed. In particular, there are frequently long periods of very low or zero water use with occasional periods of high use. In Perth high use is usually associated with the watering of gardens in periods of hot dry weather. This weather affects all Perth in essentially the same manner and hence has the tendency to make high demand *more* simultaneous across all services.

The distribution of demand of services at times of peak demand is frequently assumed to be normal although there is relatively little evidence for this. A normal distribution is clearly only an approximation and a poor one at that since it predicts that some services will have negative demand! However this is only a problem if the variation (as measured by the standard deviation) is significant compared with the mean.

The advantage of the normal distribution approximation is that it is mathematically the most tractable, especially when considering several services at once. In fact concepts such as correlation are mathematically straight forward only for the normal distribution.



**Figure 1.2 :** An illustration of the Central Limit Theorem with a distribution for one service being negative exponential with a probability density function  $f(x) = e^{-x}$ . Simulated histograms show the distributions for 1, 2, 4, 8 and 16 services.

While a single service might not have a distribution of demand which is close to normal, a group of services may have a demand which is close to normal. This is a result of the *Central Limit Theorem* which states that under quite wide conditions distributions of averages tend to normality as the number of variables being averaged grows large. This is illustrated in Figure 1.2. As a result, a diversity curve based upon the assumption of normality may be a good approximation of reality for moderate to large numbers of services while being very poor for small numbers of services.

## 1.3 Simultaneous Demand

The simplest model is to assume that services are totally independent – that is, the demand by one service is not statistically related to the demand by other services. The next would be to assume that there is a fixed dependence between all services,

irrespective of separation. A more complex model might assume that adjacent services are more closely related to each other than distantly separated ones. The main problem here is the definition of *closely related*.

The engineering definition of close must be that two services are closely linked by the reticulation network. This would tend to be similar to geographical proximity but not always so. It is also possible (though perhaps unlikely) that two services may be close in the engineering sense but very different in the aspects which affect water usage. For example, an old single residence on a large block with elderly residents may be adjacent to a new townhouse unit with virtually no garden. Here physical proximity implies very little similarity.

The result of this is that there is no clear concept of how services should be grouped in an analysis of diversity. To some extent the problem is avoided through insufficient data being available to distinguish between different models.

If the distribution of demand is assumed to be normal, the natural measure of dependence between services is the correlation. This is convenient since it is readily understood and measured.

#### 1.4 What is Maximum Demand?

Once more than one service is being considered, the concept of *maximum demand* changes. For one service it is based upon physical constraints and what is considered reasonable for a consumer to expect. For a very large number of services it is adequate to use the average demand. The problem comes with an intermediate number of services where a probabilistic approach is required, and it is necessary to consider the *maximum probable demand*. This is usually based upon a specified upper quantile of the distribution of possible demand. For example it might be a level which will only be exceeded 5% or 1% of the time.

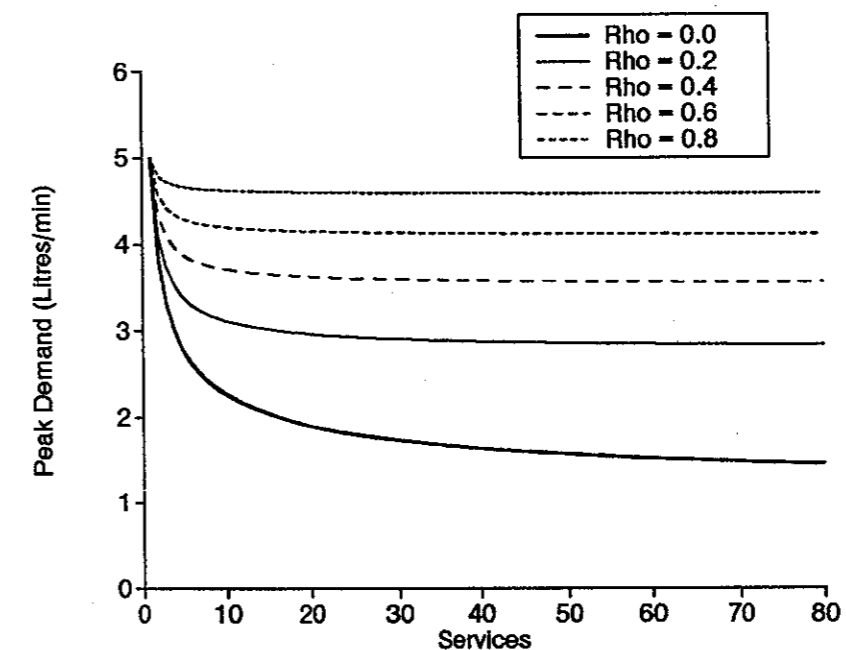
This statement is misleadingly simple. Saying that a level is exceeded *only 5% of the time* could mean

- 5% of all the time;
- at most once during 5% of the peaks; or
- during 5% of the peak period.

It would also be possible to consider the degree by which the level is exceeded. The ideal specification is probably one which gives the allowable frequency and duration of events in which the specified level is exceeded by a given amount. No such standard exists at present and this report will not consider such issues any further.

#### 1.5 Parametric Diversity Curves

The earlier report by Data Analysis Australia (WAWA/2) examined various parametric diversity curves then used by the Water Authority of Western Australia. It was shown that the standard representation then used was based upon a mathematical error which had led to an over estimation of the average demand for intermediate numbers of services.



**Figure 1.3 :** Theoretical diversity curves based on the normal model with  $\mu = 1.4$  and  $\sigma = 1.2$ , with differing values of the correlation  $\rho$ . Note how for this model the correlation affects the horizontal asymptote.

The representation assumes

- the distribution of demand between services is normal;

- the correlation between services is a fixed value  $\rho$  irrespective of distance between services; and
- the maximum probable demand was set at the upper 0.135% quantile, corresponding to three standard deviations from the mean of a normal distribution.

The correct representation is of the form

$$\mu + 3\sigma \sqrt{\frac{1}{s} + \frac{s-1}{s}\rho}$$

where  $s$  is the number of services,  $\mu + 3\sigma$  is the maximum demand from one service and  $\mu$  is the average demand per service over the whole system. A family of such curves with varying values of  $\rho$  and fixed  $\mu$  and  $\sigma$  is shown in Figure 1.3.

### Diversity Curves

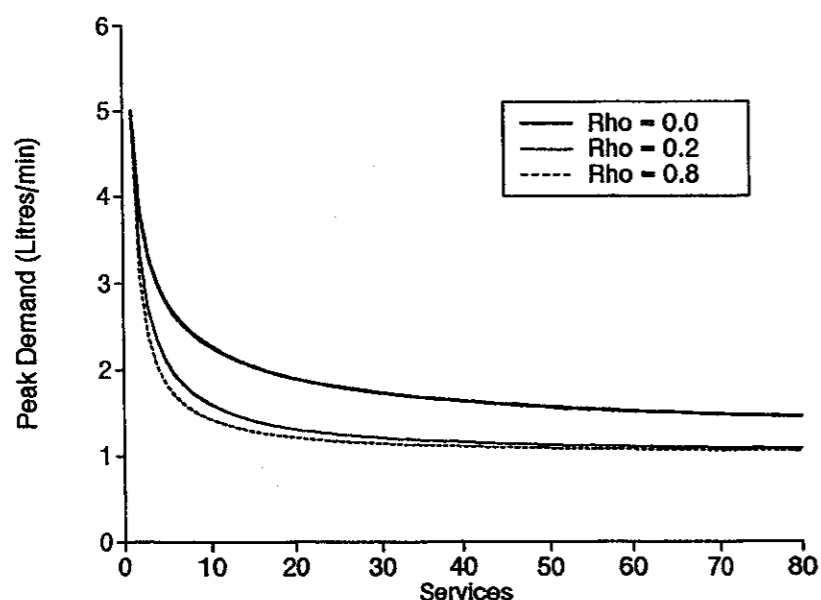


Figure 1.4 : Theoretical diversity curves based on the normal model similar to those in Figure 1.3. The one service demand and the many services demand are set to 5 and 1 respectively, with differing values of the correlation  $\rho$ .

In some respects a more useful comparison is shown in 1.4. In practice the single service peak demand is likely to be known reasonably well (based upon considerations of how water could be used) while the many or infinite service demand is also known from measurements made at key supply points. The uncertainty relates to intermediate

numbers of services. In Figure 1.4 the one service and infinite service peaks demands have been kept fixed while the correlation is varied. The effect of correlation is to lower the average peak demand from intermediate numbers of services.

### 1.6 Summary of Approach

The approach taken here is to initially obtain estimates of the parameters in the standard diversity curve given above. In a sense this simply involves determining the correlation between services at the time of system peak.

Then this representation will be tested for correctness. In particular the following questions will be directly addressed:

- Are services which are adjacent more likely to be correlated than those further apart?
- If so, to what extent can these differences be explained by structural effects such as socio-economic differences?
- Do pressure or long and short services have an effect on the peak water demand?
- Is the assumption of normality a reasonable approximation to reality?

## 2. SAMPLING DESIGN

The project required early decisions on several sampling issues. Most important were the frequency at which each service was sampled (how many samples per hour) and which services were sampled.

### 2.1 Optimal Sampling Intervals

An important issue which was addressed at the start was that of the optimal sampling interval – that is, the time between samples. If the sampling interval was too large important information might be lost. If too small, too many samples would be collected creating problems of exceeding the memory capacity of the dataloggers.

There was no information available as to what the ideal interval might be since no comparable study had been carried out in Perth before. Ultimately the decision was made on operational grounds, while preferring to err on the side of collecting too much information. One minute was thought to be the shortest interval manageable without the data becoming too voluminous.

The dataloggers used a simple data compression technology called *run length encoding*. When a sequence of sample values were the same (a 'run'), instead of each value being stored, the first would be stored together with a count giving the number of repetitions. This approach was expected to be very efficient in recording the long periods of zero water usage.

The sample values recorded by the dataloggers were actually the number of impulses from the meter during the one minute period. This had the potential to interact adversely with the data compression method. For example if a household had a slow leak which corresponded to  $1\frac{1}{2}$  impulses per minute, the sequence of data values would be 1, 2, 1, 2, 1, 2, 1, 2 and so on. The compression algorithm could not recognise and efficiently store this.

### 2.2 Selection of Services

A total of 84 domestic single residential services were required for the study. Since the major aim of the study was to examine diversity, it was essential to have the services

grouped into clusters so that the correlation (or lack of it) between adjacent services could be measured. This need coincided with the desire to minimise the travel demands which would have come from having the survey services scattered randomly through the metropolitan area.

In addition there was a need to consider the effects of high and low socio-economic groups. These might be expected to have different attitudes to the cost of water usage.

Finally there were some physical considerations in the supply of water to the services. Some regions have a high pressure making it easier to consume more water and increasing the maximum possible peak flow while others have a lower pressure. Secondly each service is either 'short' – being served by a main on the same side of the street and hence having only a short length of small diameter pipe – while others are 'long' – being served by a main on the other side of the street. Short and long services are expected to have different flow characteristics since long services have a higher head loss and hence reduced pressures.

In summary the survey design had to take into account:

- high, medium and low socio-economic groups;
- high and low pressure regions;
- short and long services;
- the use of groundwater bores; and
- adjacent and distant services.

The final design of the sample aimed to have twelve clusters of seven services each. Each cluster had at least three each of short and long services. Six clusters were high pressure and six low. For each pressure, two clusters were chosen for each socio-economic group.

In several instances clusters were merged due to the constraints in setting up the sample. The details of the clusters are shown in Table I and further information is contained in Appendix A.

**Table I**

Details of sampling clusters.

	<i>Street</i>	<i>Service Type</i>	<i>Bore</i>	<i>Pressure</i>	<i>Station Number</i>
<b>KARAWARA</b>	Wandarra Close	Short	N	High	4
	Wandarra Close	Short	N	High	7
	Boongala Close	Long	N	High	17
	Lurnea Place	Short	N	High	18
	Wandarra Close	Long	N	High	27
	Lurnea Place	Long	N	High	33
	Boongala Close	Short	N	High	44
<b>MANNING</b>	Parsons Way	Long	N	High	37
	Cloister Ave	Long	N	High	48
	Marsh Ave	Short	N	High	54
	Cloister Ave	Short	Y	High	56
	Cloister Ave	Short	N	High	63
	Cloister Ave	Long	Y	High	66
	Marsh Ave	Short	N	High	67
<b>KOONDOOLA</b>	Waddington Cres	Long	N	Medium	1
	Meredith Way	Long	N	Medium	2
	Brinkley Cres	Long	N	Medium	3
	Waddington Cres	Long	Y	Medium	10
	Butterworth Ave	Long	N	Medium	12
	Thake Court	Short	Y	Medium	14
	Meredith Way	Short	N	Medium	20
	Butterworth Ave	Long	N	Medium	29
	Meredith Way	Short	N	Medium	38
	Waddington Cres	Short	N	Medium	40
	Waddington Cres	Long	N	Medium	51
	Brinkley Cres	Long	N	Medium	53
	Waddington Cres	Short	N	Medium	82
	Thake Court	Short	N	Medium	85
<b>WATERFORD</b>	Tullamore Close	Short	Y	High	5
	Kilrush Place	Short	N	High	6
	Kilrush Place	Short	Y	High	15
	Tullamore Close	Short	N	High	16
	Kilkenny Circle	Long	N	High	25
	Kilrush Place	Short	N	High	26
	Kilkenny Circle	Long	N	High	35
	Carrick Way	Long	N	High	36
	Kilkenny Circle	Long	Y	High	46
	Tullamore Close	Short	N	High	47
	Kilkenny Circle	Long	Y	High	55
	Kilkenny Circle	Long	N	High	65
	Kilkenny Circle	Short	N	High	75
	Carlow Circle	Short	N	High	83

**Table I (continued)**

Details of sampling clusters.

	<i>Street</i>	<i>Service Type</i>	<i>Bore</i>	<i>Pressure</i>	<i>Station Number</i>
<b>BALGA</b>	Mirrabooka Ave	Short	N	Low	11
	Hornsey Way	Long	N	Low	13
	Mirrabooka Ave	Short	N	Low	21
	Mirrabooka Ave	Short	N	Low	22
	Hornsey Way	Long	N	Low	30
	Hornsey Way	Long	N	Low	41
	Hornsey Way	Long	N	Low	50
	Mildmay Street	Short	N	Low	60
	Mildmay Street	Short	N	Low	71
	Mirrabooka Ave	Short	N	Low	72
	Mildmay Street	Long	N	Low	79
	Mildmay Street	Short	N	Low	80
	Hornsey Way	Long	N	Low	81
	Mildmay Street	Short	N	Low	87
<b>DUNCRAIG</b>	Marri Road	Short	N	Low	19
	Marri Road	Long	N	Low	23
	Marri Road	Short	N	Low	24
	Marri Road	Short	N	Low	32
	Marri Road	Short	N	Low	49
	Marri Road	Long	N	Low	57
	Marri Road	Short	N	Low	58
	Acacia Way(cnr)	Long	N	Low	62
	Marri Road	Short	N	Low	64
	Marri Road	Long	N	Low	68
	Marri Road	Short	N	Low	73
	Marri Road	Long	N	Low	74
	Duncraig Road	Long	N	Low	77
	Marri Road	Short	N	Low	84
<b>HILLARYS</b>	Venus Way	Long	N	Medium	28
	Hicks Way	Long	N	Medium	34
	New England Drive	Short	N	Medium	39
	Sporing Way	Short	N	Medium	42
	New England Drive	Long	N	Medium	43
	Sporing Way	Long	N	Medium	45
	New England Drive	Short	N	Medium	52
	Sporing Way	Short	N	Medium	59
	Solander Road	Long	N	Medium	61
	Venus Way	Short	N	Medium	69
	Venus Way	Short	N	Medium	70
Sporing Way	Short	N	Medium	76	
Hicks Way	Long	N	Medium	78	
Venus Way	Short	Y	Medium	86	

### 3. DATA MANAGEMENT

The management of data from 84 households recorded every minute for over two months was a significant consideration. The data was provided to Data Analysis Australia as compressed files from the HYDSYS water data system which was limited in the number of services which could be treated together.

The processing was done mainly on PC compatible computer with a 50 MHz 486DX processor, 16 Mbyte of RAM and a 425 Mbyte hard disk. Additional work was carried out on a Sony Unix workstation which had a large workspace version of the time series package TSA 1.77 (Henstridge, 1982).

Since many of the analysis procedures were computationally intensive and required special purpose programs, a specialised database was created using cached direct access binary files. This allowed the full dataset to be accessed efficiently by Fortran programs, with proper missing value management. The database was optimised for accessing a number of services simultaneously since a major part of the study involved correlating the demand at different services. The final size of the database was approximately 56 Mbytes.

#### 3.1 Optimal Sampling Frequency

A first step in the analysis was the examination of the sampling frequency. If it was not necessary to use one minute data in the following stages considerable computational savings could be made.

A recommended method of examining the adequacy of sampling is through estimates of the spectral density. These give the decomposition of the variation or information in the data according to frequency - it is the time series equivalent of the analysis of variance. It is possible to evaluate the spectrum up to a frequency half that of the sampling rate. In this project the sampling rate was 60 per hour so the spectra could be evaluated at frequencies up to 30 cycles per hour.

Non-standard techniques had to be used due to the highly skewed nature of the data. In particular the statistical properties at very low flow rates were expected to be different from those at high flow rates since the nature of water use would be different. Hence a 'threshold model' was used where the statistical properties are assumed to

depend upon the flow level. (Such models have been used in other areas of time series by authors such as Priestly and Tong.)

For our purposes, three bands were set - 0 to 5 litres per minute, 5 to 10 litres per minute and above 15 litres per minute. In each of these bands and for each service the spectral densities were calculated via the autocorrelation functions, using lags up to 60 minutes as follows:

- [1] The autocorrelations  $\hat{\gamma}_j$  were estimated for lags  $j$  from 0 to 60 by

$$\hat{\gamma}_j = \frac{\sum (x(t) - \mu)(x(t+j) - \mu)}{\sum (x(t) - \mu)^2}$$

where  $\mu$  was the mean of the data in that band.

- [2] The Fourier transform of the autocorrelation function was then calculated to give the spectrum:

$$f(\omega) = \sum_{j=-60}^{60} e^{ij\omega} w_j \hat{\gamma}_j$$

where the  $w_j$  were a set of weights designed to ensure stability in the estimates. e.g. (Koopmans, 1975)

The first step was carried out using a Fortran program and the second in TSA 1.77. A representative set of spectra for Station 1 is given in Figure 3.1 and full details are available separately.

It is clear from these spectra that there is very little information at frequencies above 10 cycles per hour. Hence no significant information would be lost through aggregating the data to three minute averages.

In future projects the sampling interval could be increased to three minutes (corresponding to 20 samples per hour) without loss of information. This would result in some savings in data collection and major savings in data management costs.

Note that since the dataloggers used a compression technique based on run length encoding it is not simple to quantify how the increased sampling interval increases the capacity of the loggers. It is unlikely that the capacity would increase by a factor of more than two and it may be somewhat less. It should however be possible to measure the effect on the existing data.

In future projects it may be worth examining the compression methods of the dataloggers using some of the series obtained from this project. In particular algorithms which can compress patterns of several data points should be considered.

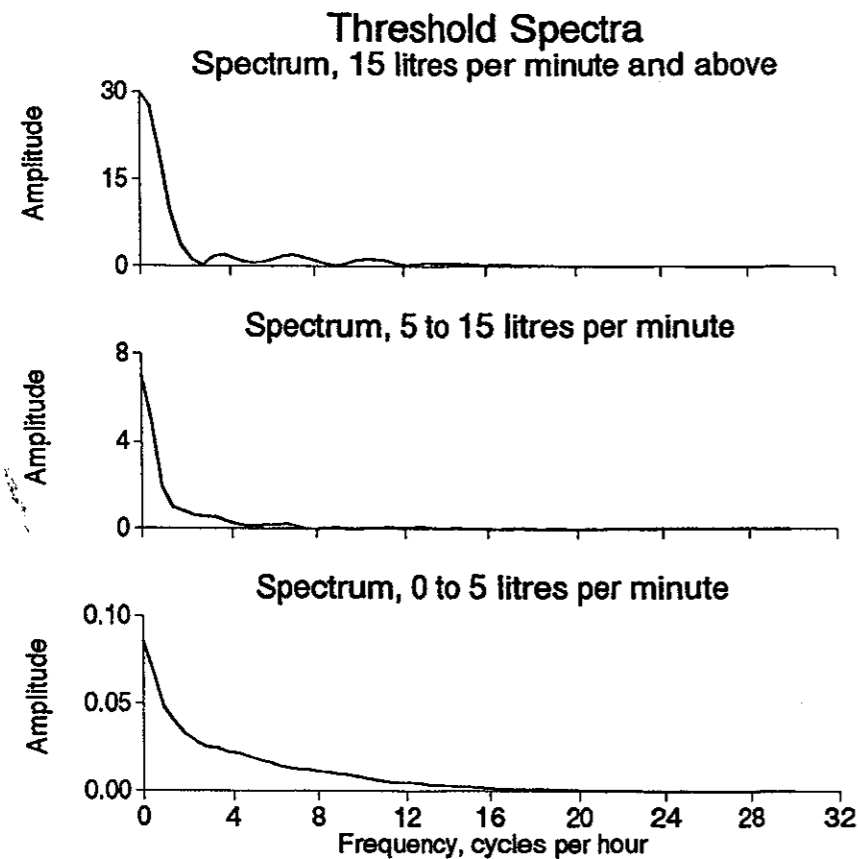


Figure 3.1 : Threshold spectra for the data from Station 1. The vertical axis in each case measures components in the variance.

### 3.2 Aggregation

All further work in this report uses three minute averages unless otherwise indicated. This was done for reasons of computational efficiency and because it overcomes some minor problems resulting from the measurement of flow by counting discrete pulses.

## 4. WATER USE THROUGH THE STUDY PERIOD

The summer of 1991/92 did not have any periods of prolonged hot dry weather which is usually associated with very high water consumption. Hence, none of the data collected in this study directly covers the peak demand situation for which the pipe system is designed.

This does not mean that the data collected is not relevant to the study of diversity in this peak demand situation. In fact, if we insisted that only data which corresponds to the historical peak demand should be used, then that data set would be so small as to be statistically meaningless. Rather, it is important to understand the system which produces the peak demand and then relate the existing data to that situation. This should mean that a substantial body of information can be used and the diversity properties extrapolated to the peak demand.

Historically, the peak demand has occurred at 7.00 pm after a period of hot easterly winds. During this study, the peak demand generally occurred about 6.30pm. This change is thought to be primarily due to the introduction of a daylight saving trial over the 1991/92 summer. In addition, the peak 6.30 demand is associated with a high consumption for the whole day. Hence, there are several items which should be considered in the analysis.

- The average 6.30 pm demand in our sample.
- The average daily consumption in our sample.
- The whole of Perth consumption for the day.
- Maximum temperature.
- Rainfall
- Evaporation

Table II gives these items for the 111 days of the study. The summary information is displayed graphically in Figures 4.1 - 4.3. It can be seen that there was a slight downwards trend in the average temperature during the study. As is typical during a Perth summer, there were very few instances of rain but one of these (9th February) was extreme with 120.6 mm. of rain reported in the 24 hours to 9.00 am.

Table II

Summary information for each day in the study.

Day	Date	Average Consump. /service litres	6.30 flow (12 min.) l./min.	6.30 flow (24 min.) l./min.	Maximum consump. litres	House of max. consump.	Maximum temp. °C	Rain mm	Evap. mm	Perth consump. /service l.
1	12-Dec-91	1710.9	1.66	1.76	2203.3	26	27.7	0	5.2	2453.8
2	13-Dec-91	1731.9	2.67	2.73	2135.3	25	25.5	0	8	2370.1
3	14-Dec-91	2050.5	2.06	2.13	2407.3	45	28.5	0	7.2	2582.1
4	15-Dec-91	2736.6	3.91	3.84	2845.6	76	34.8	0	6.4	2955.6
5	16-Dec-91	2142.3	4.6	4.97	2620.4	62	40.9	0	8	3426.6
6	17-Dec-91	2429.1	4.11	3.93	4009.8	26	39.8	0	12.6	3005.6
7	18-Dec-91	1522.2	0.81	0.81	2892.7	45	23.5	0.05	8.6	2034.5
8	19-Dec-91	1724.7	2.14	1.99	3158.5	12	23	0.05	3.6	2414.8
9	20-Dec-91	2100.0	2.73	3.14	2225	7	27.8	0	6.6	2635.8
10	21-Dec-91	2399.1	3.89	3.87	3073	32	38.2	0	5.8	2888.6
11	22-Dec-91	2172.3	2.05	2	2025.7	57	25.8	0	6.6	2556.8
12	23-Dec-91	1911.6	4.7	4.5	2587.2	52	29.5	0	3.8	2723.4
13	24-Dec-91	1070.1	0.59	0.62	2303.7	65	24.9	4.2	7.2	1297.2
14	25-Dec-91	755.4	0.33	0.41	2009.3	52	23.6	12.4	2.8	1009.4
15	26-Dec-91	1006.8	0.47	0.54	2025.5	52	23.8	14	3.8	1368.9
16	27-Dec-91	1218.6	1.5	1.48	2192.8	26	24.2	0.2	5.2	1698.8
17	28-Dec-91	1543.5	4.17	3.97	2179.7	25	25.9	0	5.4	1907.7
18	29-Dec-91	1944.0	1.94	1.91	2918.2	45	27.8	0	7	2235.6
19	30-Dec-91	1731.6	2.57	2.51	3376.5	57	30.7	0	6.4	2465.8
20	31-Dec-91	1446.3	1.91	1.97	2052.5	12	24.6	0	6.6	1831.2
21	1-Jan-92	1566.9	2.27	2.21	2250	82	23.8	0	5	1879.3
22	2-Jan-92	1693.2	2.59	2.64	2406.7	26	25	0	4.6	2230.2
23	3-Jan-92	2086.8	5.21	4.98	4244.5	45	34	0	6.2	2624.9
24	4-Jan-92	2035.2	2.33	2.22	2229	75	36.1	0	7.8	2653.7
25	5-Jan-92	2022.9	2.4	2.67	2871.5	29	33.6	0.4	6.8	2736.8
26	6-Jan-92	2111.7	3.94	3.91	2206	71	35.5	0	9.2	3166.9
27	7-Jan-92	2116.2	4.43	4.38	2725	52	36.3	0	9.4	3052.7
28	8-Jan-92	2204.4	4.74	4.75	2958.6	52	36.4	0	8.6	3032.0
29	9-Jan-92	1802.4	3.6	3.56	2331.7	52	31.9	0	8	2751.1
30	10-Jan-92	1773.3	4.92	4.74	2393.7	16	36	1	9	2483.6
31	11-Jan-92	2182.2	2.93	2.87	3440.1	42	37.6	0	8	2906.9
32	12-Jan-92	2142.6	3.13	3.37	2575.3	57	34.3	0	8	2941.7
33	13-Jan-92	2225.4	3.57	3.63	3117.8	71	34.7	0	8.2	3021.3
34	14-Jan-92	1980.6	3.36	3.41	3597.1	45	32.5	0	8.8	2834.0
35	15-Jan-92	1977.6	3.39	3.57	2133.2	7	35.8	0	8	3050.6
36	16-Jan-92	2154.6	3.88	3.89	3555.8	44	40.7	0.05	7.6	3209.1
37	17-Jan-92	1756.2	1.71	1.51	2070.3	75	28.3	0	7.6	2726.4
38	18-Jan-92	1643.1	2.43	2.33	3414.3	44	26.1	0	5.8	2314.4
39	19-Jan-92	1912.8	2.55	2.39	2221.7	52	24.1	0	5.4	2451.5
40	20-Jan-92	1293.3	1.29	1.35	2065.5	52	23.5	0	7.2	2149.0
41	21-Jan-92	1335.3	2.04	2.14	2130.5	52	23.7	0.05	3.2	2106.7
42	22-Jan-92	1399.5	4.5	4.47	2130.2	52	25.5	0.4	4.4	2290.9
43	23-Jan-92	1945.8	3.06	3.21	2124.3	75	30.2	0	6.4	2725.6
44	24-Jan-92	1615.2	3.32	3.47	2195.2	52	34.8	0	8	2837.4
45	25-Jan-92	2026.8	2.41	2.62	2215.2	75	34.1	0	8	2849.8
46	26-Jan-92	2047.2	2.84	2.96	3949.5	45	36.7	0	7.8	2857.7
47	27-Jan-92	1437.0	1.77	1.76	2338.8	52	34.7	0	9.6	2522.6
48	28-Jan-92	1756.8	2.14	2.16	2723.7	26	36	0.6	5.8	2961.2
49	29-Jan-92	2046.3	4.71	4.65	2840.3	83	36	0	8.4	3063.0
50	30-Jan-92	2018.7	3	2.92	2876.7	83	39.1	0	8.6	3068.3
51	31-Jan-92	2100.6	2.52	2.45	2759.2	26	38.7	0	9.6	3046.4
52	1-Feb-92	1765.2	2.92	3.07	2318.8	44	31.2	0	8	2720.7

53	2-Feb-92	1691.4	2.27	2.45	2662.7	25	28.1	0	7.8	2627.4
54	3-Feb-92	1466.1	3.83	3.83	1991.5	26	26.6	0	8	2397.2
55	4-Feb-92	1460.4	1.76	1.78	2195.7	43	26	0	5.6	2529.8
56	5-Feb-92	1630.5	2.07	2.16	2116.2	7	30.5	0	6.6	2685.3
57	6-Feb-92	1180.8	0.36	0.56	2055.9	24	32.5	0	7.2	1869.9
58	7-Feb-92	1271.1	1.77	1.71	3652.3	35	28.2	2.6	3.4	1934.8
59	8-Feb-92	940.2	0.54	0.48	2954.5	32	22.9	1.6	3.4	1234.2
60	9-Feb-92	821.7	0.95	0.77	3728.5	32	26.9	120.6	0	1297.7
61	10-Feb-92	975.3	0.93	0.88	2983.7	83	26.5	0	3.8	1515.2
62	11-Feb-92	1072.5	2.64	2.63	1633.3	52	30.7	0	6.4	1763.7
63	12-Feb-92	1346.1	1.59	1.75	2469	42	38.1	0	7.6	2018.7
64	13-Feb-92	999.9	1.78	1.87	2140.8	44	27	0.4	5.4	1667.1
65	14-Feb-92	1136.1	0.88	0.99	1983.5	75	26.6	0.4	6	1688.7
66	15-Feb-92	672.6	0.74	0.64	1516	52	26	5.8	3.8	1339.7
67	16-Feb-92	874.8	0.4	0.45	1645.7	52	24.7	0	2.6	1553.5
68	17-Feb-92	958.2	1.22	1.15	2088.7	75	23.7	0.05	4.2	1753.9
69	18-Feb-92	1227.0	2.72	2.73	1633.2	16	25.4	0	3.6	1987.0
70	19-Feb-92	1173.0	2.05	2.18	2000.5	75	29.4	0	5.6	2044.1
71	20-Feb-92	1340.1	2.52	2.41	2014.5	75	29.4	0	4	2046.2
72	21-Feb-92	1299.3	1.05	1.13	1753	65	25.4	0	6.8	1985.4
73	22-Feb-92	1533.0	1.43	1.41	1687.2	82	29.5	0	6.4	2189.5
74	23-Feb-92	1496.4	4.06	4.1	2053.8	75	31.6	0	6.2	2410.7
75	24-Feb-92	1761.0	4.08	4.1	2156.7	75	34.2	0	5.6	2683.0
76	25-Feb-92	1745.7	6.04	5.93	2186.4	75	34	0	8.2	2636.8
77	26-Feb-92	1762.8	3.92	4.16	2603.5	26	35.5	0	9.8	2762.3
78	27-Feb-92	1977.9	3.66	3.64	2174.7	75	38	0	10	2823.2
79	28-Feb-92	1576.2	2.2	2.53	2004.2	75	33.4	0	7.8	2386.4
80	29-Feb-92	1463.4	1.99	2.12	2022.8	75	29.2	0	5.8	2294.0
81	1-Mar-92	1773.0	2.09	2.18	2583.9	76	28.3	0	7	2170.9
82	2-Mar-92	1541.7	2.04	1.99	2188.5	7	31.9	0	4	2368.6
83	3-Mar-92	1173.6	2.05	2.09	1823.2	52	24.6	0	7	2099.8
84	4-Mar-92	1563.9	1.7	1.89	2324.7	75	25.3	0.05	6.8	2176.1
85	5-Mar-92	1458.3	2.01	2.09	1930	75	28.8	0	5.4	2298.5
86	6-Mar-92	1435.8	3.63	3.5	2052	75	29.5	0	6	2254.1
87	7-Mar-92	1729.5	2.74	2.7	2159.5	75	29.8	0	4.2	2364.2
88	8-Mar-92	1713.6	1.67	1.81	2144.5	75	30	0	4.8	2382.6
89	9-Mar-92	1158.3	2.09	2.17	1568.8	26	26.5	0	5.8	2164.5
90	10-Mar-92	1061.4	1.68	1.49	1762.7	52	28.5	1	5	1800.9
91	11-Mar-92	1456.5	2.78	2.73	2596.3	12	31.1	0	5.6	2291.3
92	12-Mar-92	1680.3	2.98	2.8	3246.8	32	30.3	0	5.6	2263.8
93	13-Mar-92	1629.3	2.93	2.75	3093.7	7	28.2	0	7	2160.2
94	14-Mar-92	933.6	1.1	1.16	1535.2	52	21.8	0	5.2	1655.5
95	15-Mar-92	1505.7	1.78	1.91	2086.5	52	24.6	0.4	2.8	1932.0
96	16-Mar-92	936.3	0.89	0.78	5186.1	29	23.8	0.05	6	1649.0
97	17-Mar-92	844.5	0.68	0.76	1616	16	25.5	0.6	3.8	1353.1
98	18-Mar-92	669.3	0.93	0.89	1473.5	52	28.8	25	2	1408.5
99	19-Mar-92	706.2	0.44	0.5	1684	52	24.6	10	3.8	1249.7
100	20-Mar-92	724.5	0.29	0.5	1596.5	16	24.7	8	1	1234.1
101	21-Mar-92	732.6	0.55	0.53	1485.3	52	23	0.8	2.4	1232.7
102	22-Mar-92	840.0	1.44	1.38	1837	26	25.4	0.05	1.6	1493.4
103	23-Mar-92	966.3	1.15	1.22	1822.5	65	29.9	0.05	4.8	1807.6
104	24-Mar-92	1046.1	2.1	1.95	1727	26	28.7	0	3.6	1792.0
105	25-Mar-92	783.3	1.12	1.18	1538	52	24.8	0	4.4	1587.5
106	26-Mar-92	1017.6	2.67	2.51	1805.3	26	25.2	0.05	4.6	1793.9
107	27-Mar-92	1202.4	1.27	1.44	2039.3	75	27	0	6	1864.9
108	28-Mar-92	1404.9	1.94	1.92	2529.7	44	27.8	0	4.4	2022.5
109	29-Mar-92	1312.5	2.62	2.34	1897.3	25	29.1	0	4	2087.5
110	30-Mar-92	1091.1	2.28	2.22	1951.8	75	25.6	0	5	1850.7
111	31-Mar-92	1236.9	1.58	1.43	2214.9	75	31.8	0	3.6	1998.1

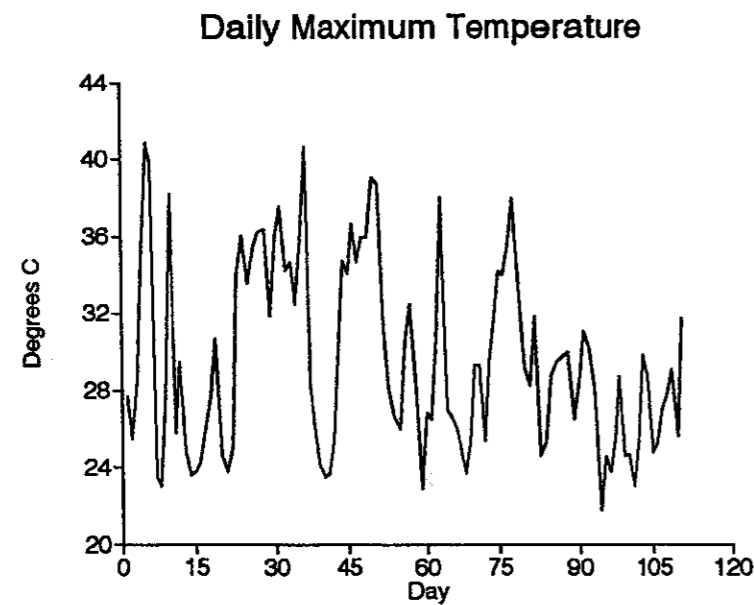


Figure 4.1 : Daily Temperatures in Perth.

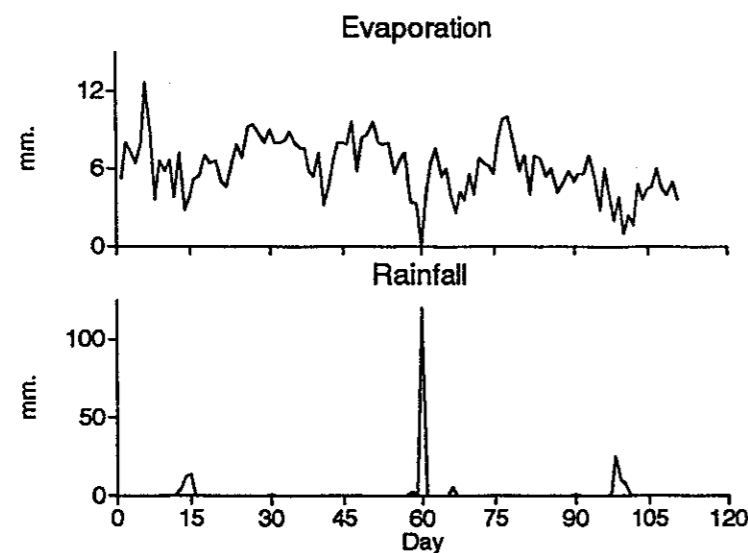


Figure 4.2 : Daily evaporation and rainfall for Perth.

It is apparent that the summer of 1991-92 was the hottest in the beginning of the study period and declined slowly. In fact the hottest period with the peak water consumption (measured as the maximum Perth daily consumption) occurred unexpectedly just before the study period.

#### 4.1 The Sample and Perth

Firstly it is worth investigating the relationship between our samples of households

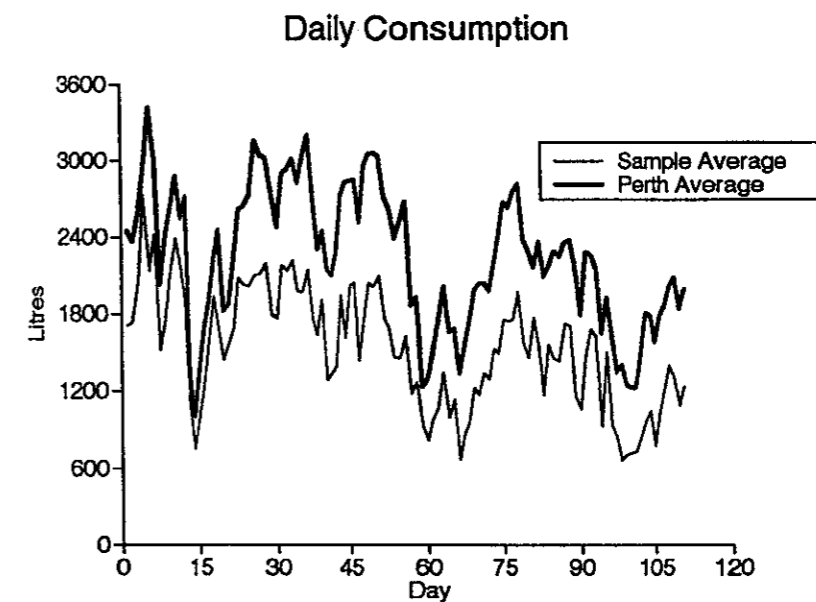


Figure 4.3 : Daily total average consumptions for the sample and the Perth Region.

and all of Perth consumption. In doing so it must be realised that Perth consumption includes a significant non-domestic component and hence the greater consumption. The Figure 4.4 is a plot of the sample and Perth consumption per service. It can be seen that the correlation is quite high ( $\rho = 0.919$ ).

This indicates that our sample is probably a reasonably good indicator of Perth households, and since the relationship between the Perth consumption and our house sample consumption is so good, we could use the Perth consumption during a peak demand period to predict the average consumption of our sample during such a peak demand period. This should be further refined since the sample is known to over represent long services and the high and low pressures. (See section 5.2.)

#### 4.2 Demand by time of Day

With the exception of the Christmas holiday period daily demand patterns did not change during the study period.

The average demand by time of day is shown in Figure 4.6. It can be seen that two peaks occur – the morning at about 7 a.m. and in the evening around 6.30 p.m. The evening peak is the higher one but only by a small margin.

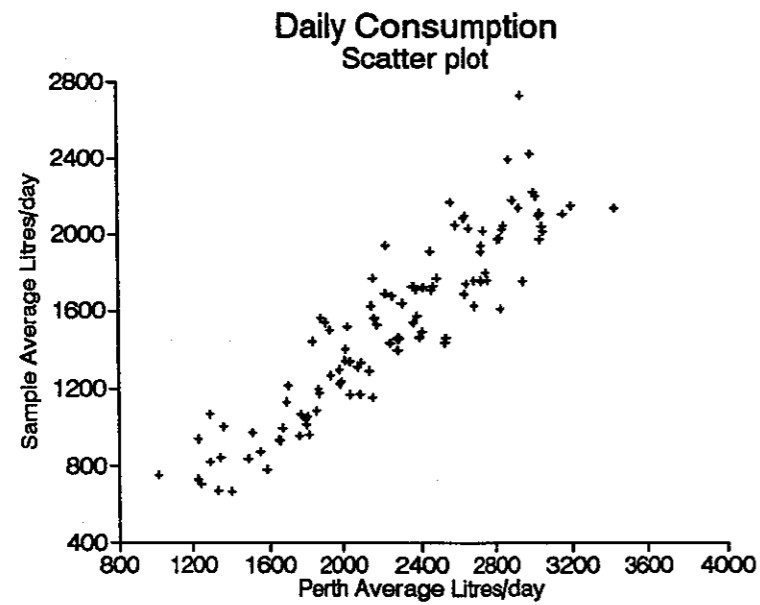


Figure 4.4 : Scatterplot of daily total average consumptions for the sample and the Perth Region.

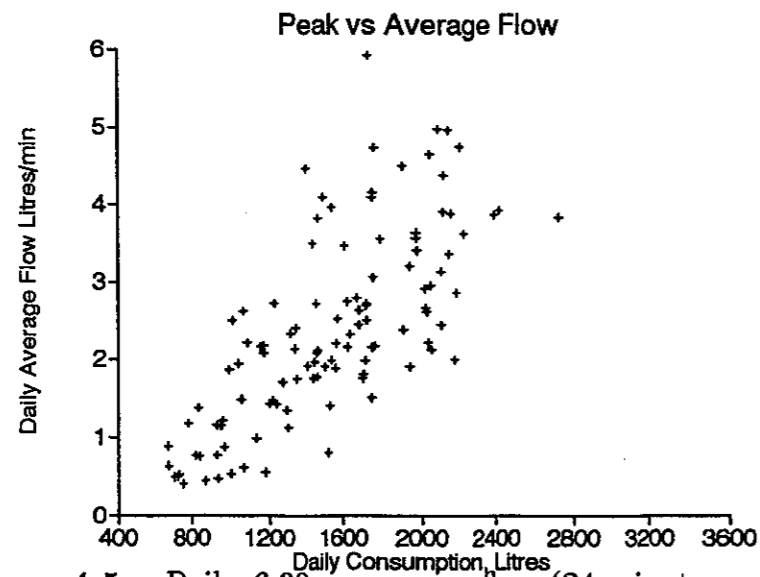


Figure 4.5 : Daily 6.30pm average flow (24 minute peak width) versus daily average flow.

### 4.3 Explanatory Relationships for Demand

The evening peak is the demand for which reticulation systems tend to be designed. Hence it is important to consider how the peak demands in this study may relate to longer term peak demands. It is commonly accepted that the demand is strongly affected by the weather. In addition, it is reasonable that the peak demand and the total demand for the day are related. Thus an investigation of the relationship between the demand and the weather is relevant.

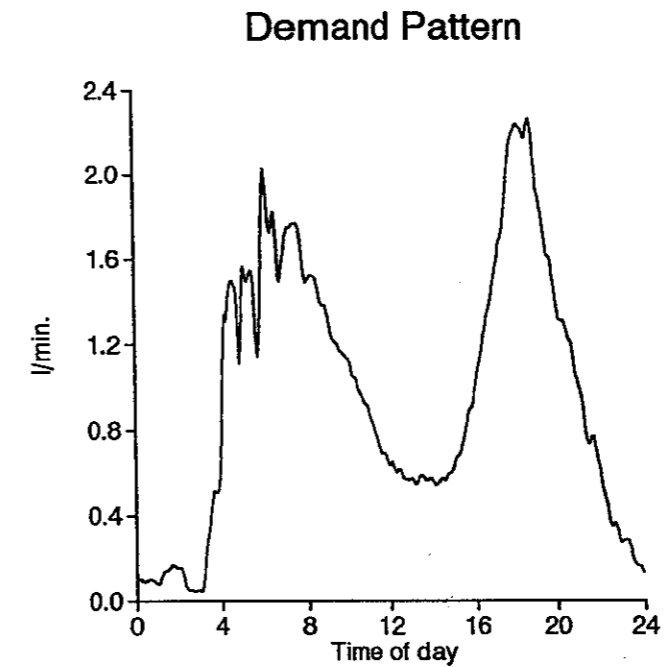


Figure 4.6 : Average demand by time of day over the study period. The irregularity at the top of the evening peak cannot be considered statistically significant. Hence the peak is best described as being centred on 6.30 pm and approximately one hour in width.

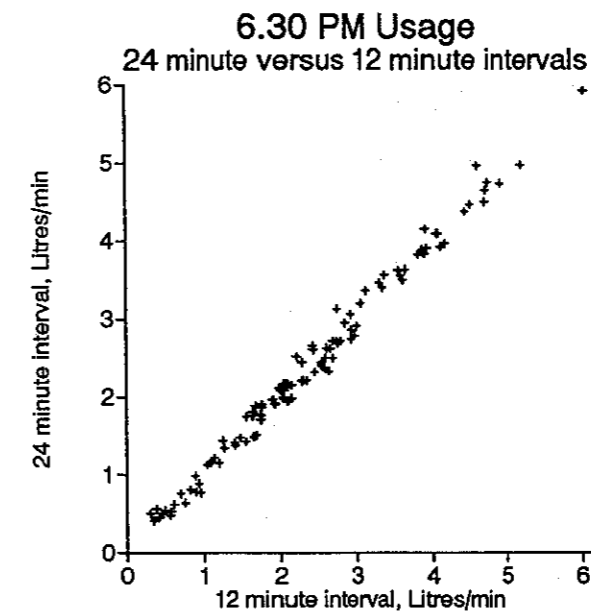


Figure 4.7 : Daily 6.30 pm flow, a comparison of 12 minute and 24 minute intervals.

In investigating this, it is important to consider the time span that is used in defining the peak. A major reason for doing this is to determine how critical the time of peak actually is. For this aspect of the study we considered both 12 minute and

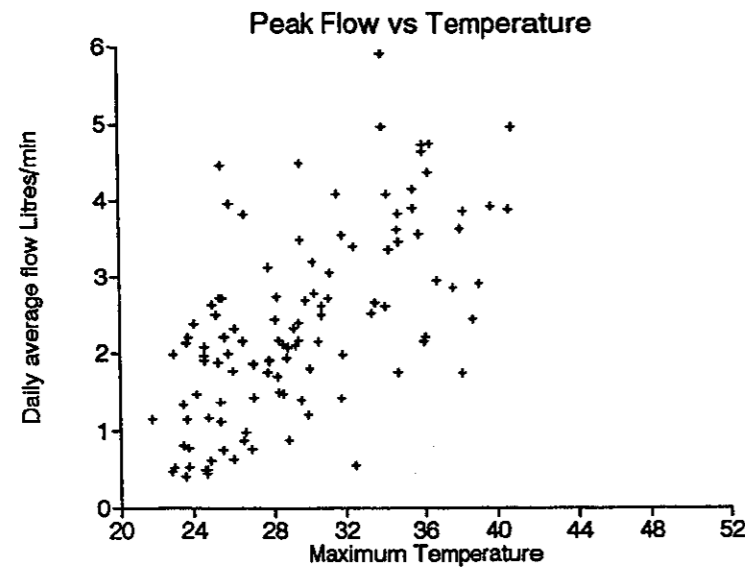


Figure 4.8 : Daily 6.30pm average flow versus temperature.

24 minute intervals centred on 6.30 pm. (One minute or three minute data would not be sufficiently stable on a small sample size such as this.) Figure 4.7 shows the relationship between the 12 minute average and the 24 minute average. It can be seen that the relationship is extremely close, hence there would be a negligible difference between using one average and the other. Hereafter in this section we are using the 24 minute average since it is marginally more stable.

Table III

Correlations between flows and temperature.

6.30 flow, 24 minute average	1.000			
6.30 flow, 12 minute average	0.994	1.000		
Average daily flow	0.727	0.713	1.000	
Maximum temperature	0.638	0.623	0.680	1.000

The relationships between the four variables discussed above - 6.30 pm flow averaged over 24 minutes and 12 minutes, the average daily flow and the maximum temperature are displayed as correlations in Table III. It can be seen that the 6.30 flows are closely related to each other but that temperature is most closely associated with average daily flow.

Time series regression techniques can be used to predict the 6.30 pm demand from the meteorological variables (temperature, rain and evaporation) and the average consumption. A number of different models were investigated interactively using the time series package TSA 1.77, evaluating each possible model for physical reasonableness as

well as statistical goodness of fit. Eventually a transfer function model was fitted as follows:

$$d_t = \beta_1 T_t + \beta_2 R_t + \eta_t + c$$

where

$d_t$  = peak demand on day  $t$

$T_t$  = Maximum temperature on day  $t$

$R_t$  = rainfall input defined by  $R_t = \alpha_1 R_{t-1} + r_t$

where  $r_t$  is the rainfall on day  $t$

$\eta_t$  = noise at day  $t$

$c$  = constant

and the noise model is

$$\eta_t = \alpha_2 \eta_{t-1} + \epsilon_t$$

where the  $\epsilon_t$  are independent normally distributed random variables.

The parameters  $\alpha_1$  and  $\alpha_2$  are called the autoregressive parameters for the rainfall input and the noise respectively and measure how smoothly they affect the demand - values close to one indicate very smooth variation. The high value for the rainfall input suggests that the effect of rainfall on demand lasts for approximately five days. The absence of an autoregressive term for the temperature input suggests that the temperature effect is short lived.  $\beta_1$  and  $\beta_2$  are effectively regression coefficients for the overall effect of temperature and rainfall respectively. Not surprisingly it is positive for temperature (increasing temperature increases demand) and negative for rainfall (increasing rainfall reduces demand).

Table IV

Parameters of the time series model for peak demand.

	Estimate	S.E.	
Autoregressive	0.1771	( 0.0994)	$\alpha_2$
Input series TEMP	0.1391	( 0.0214)	$\beta_1$
Input series RAIN(1)	-0.0157	( 0.0059)	$\beta_2$
Autoregressive	0.8335	( 0.0971)	$\alpha_1$
Constant term	-1.5518	( 0.6594)	$c$
Goodness of fit statistics			
Residual variance	0.8397		
Sum of squares	88.1639	on 105 degrees of freedom	

## 5. DISTRIBUTIONS OF DEMAND

The distribution of demand by services has two dimensions -

- 1 the variation of demand by a single service over time; and
- 2 the variation of demand by different services at the same time.

Both are relevant when considering diversity. The latter is of more direct importance since it embodies the issue of relationship between demands of different services at the same time. However the former (the univariate distribution) is important when considering the duration of peak demands.

### 5.1 Univariate Distributions - All Times

As referenced earlier, most of the time a service can be expected to have a flow rate close to zero. This is illustrated in Figure 5.1 where the cumulative distributions are shown for the months of January, February and March as well as the distribution for the day with the peak consumption during the study period, 16th December.

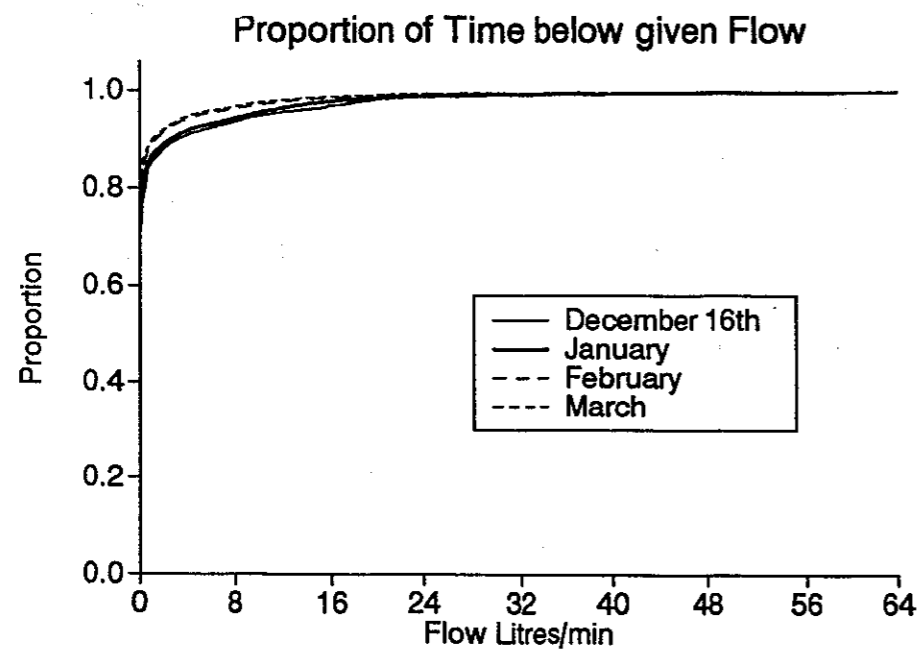


Figure 5.1 : Distribution of flow rate with respect to time.

It can be seen that 70% of the time there is no flow and 95% of the time the flow rate is less than 8 litres per minute. The lower consumption in February and March is also evident.

The distribution of flow is better illustrated if presented relative to the volume of water rather than time. Figure 5.2 shows the cumulative flow for a range of low rates. From this it can be seen that about 50% of the water volume is delivered at flow rates less than 16 litres per minute.

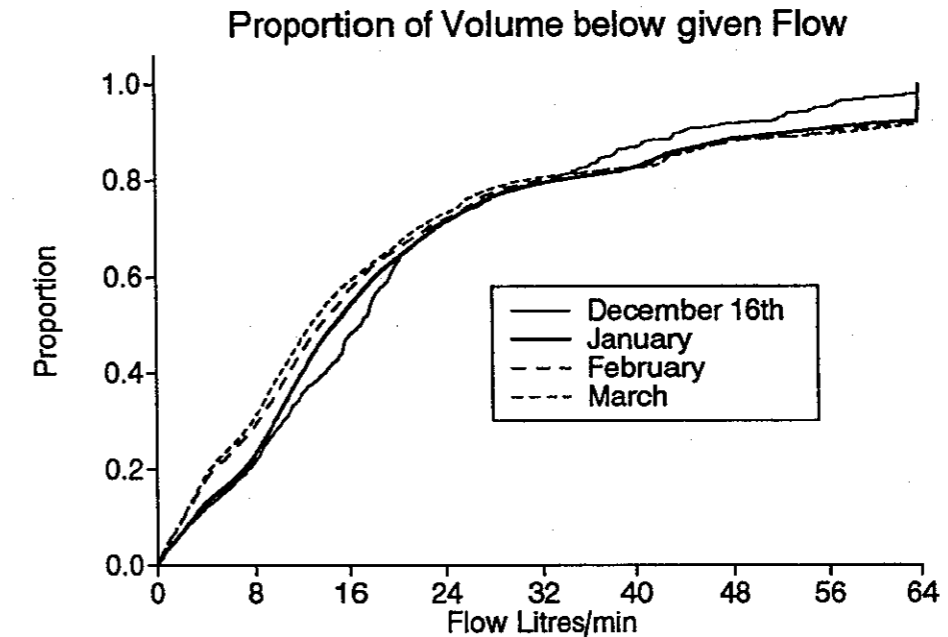


Figure 5.2 : Distribution of flow with respect to water consumed.

### 5.2 Univariate Distributions - At Peak Times

Since the reticulation network is designed with peak or close to peak demands in mind, it is more relevant to examine the distribution of demands across services restricted to such times.

The distribution of demand relevant to peak demand can only be ascertained by reference to data obtained at the time of peak demand or close to peak demand. In practical terms it is essential a means be found of using the information from times not precisely at peak demand since:

- strictly speaking the peak is only an instant giving only one data point and thus not much information; and
- the data set might not include the time of actual peak demand.

It is thus necessary to use a technique which extracts relevant information from times close to peak demand and then to apply this to the peak.

The obvious technique to attempt is based on assuming that the distribution is the same in shape but not necessarily in scale around the peak. Hence if the distributions at the times close to the peak are scaled to a common basis they can be aggregated. The scaling used here is the flow rate averaged over all services. Other scaling factors could perhaps have been used (such as the median or the maximum) but were less likely to be mathematically tractable or statistically stable.

The resulting flow rates will be called *relative flows* indicating that they are relative to the average flow rate or demand across the sample.

Before proceeding with this approach it was verified by checking that the shape of the distribution (or the scaled distribution) does not depend upon the scaling factor. Two checks were carried out:

- As noted earlier, at the time of peak demand many (around half) of the services have a zero flow rate. This is the major feature in the distribution of demand from a single service. It was checked whether the proportion of such services depended upon the scale factor.
- In a study of diversity the variability in the demand from services is critical. It was checked whether the variance between services could be related to the scale factor.

Figure 5.3 is a scatter plot of the proportion of services with zero flow plotted against the average flow. Only times when the average flow rate was greater than 4.3 l/min were considered. (This cut-off value was chosen by examining the effect of varying cut-offs. Choosing too high a cutoff leaves too few data points while too low a cut-off may contaminate the analysis with data too distant from the peak demand situation.) No pattern is evident in this plot, a fact confirmed by regression analysis. Similarly the variance of the scaled distribution between services is plotted against the average flow rate in Figure 5.4. Here regression analysis revealed a small but statistically significant downward trend in the variance with increasing average flow rate. The variance of the scaled distribution was found to decrease by 0.51 for each 1 l/min increase in average flow rate. However this is regarded as small from a practical viewpoint although perhaps deserving further study when more data becomes available.

The scaled cumulative distribution is shown in Figure 5.5 is based upon flows greater than 4.3 l/min. Note that the abscissa represents the demand scaled to have mean one. Its general shape can be compared with Figure 5.1. The substantial prob-

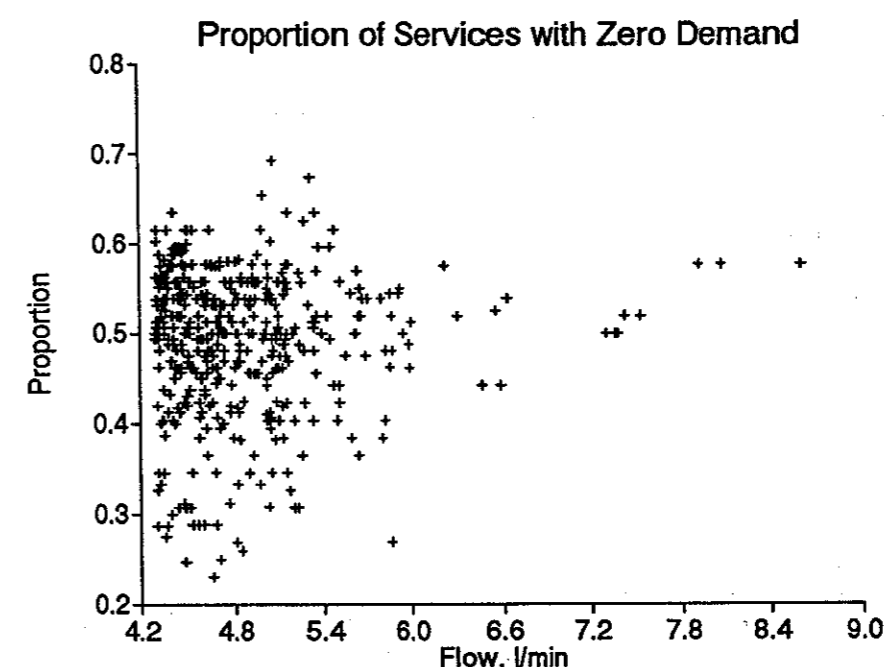


Figure 5.3 : Proportion of services with zero demand plotted against the flow rate averaged over all the services in the sample.

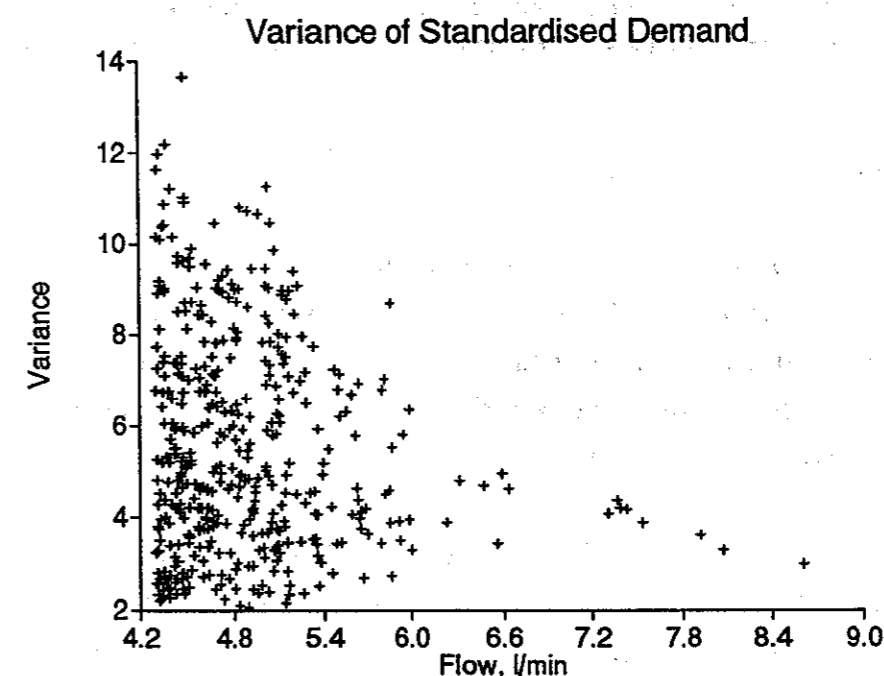


Figure 5.4 : The variance of the scaled distribution of demands from services plotted against the flow rate averaged over all the services in the sample.

ability of zero demand means that the corresponding probability density function is difficult to interpret.

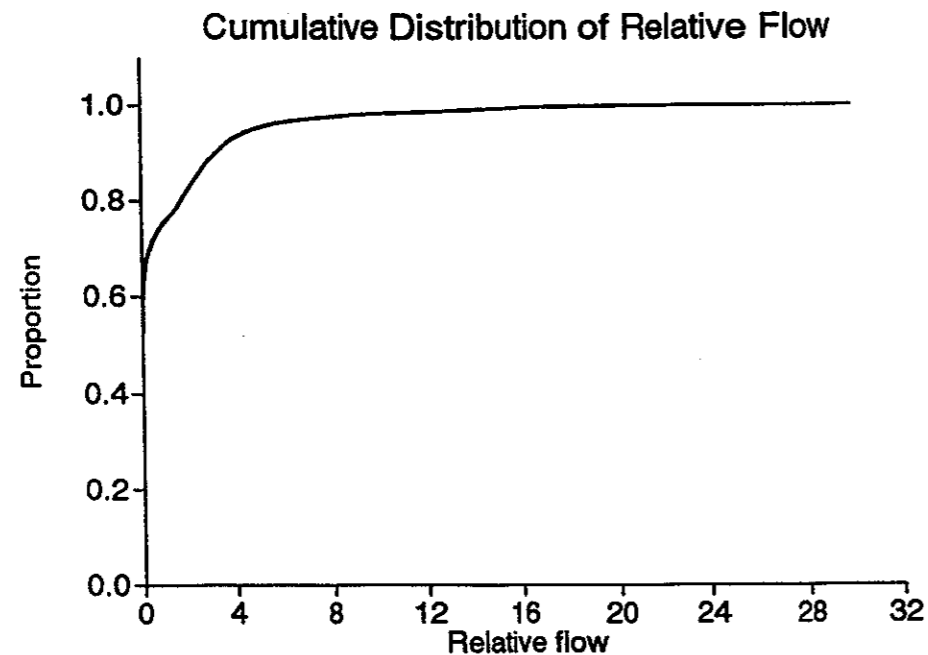


Figure 5.5 : The cumulative distribution function for the demand from a single service, scaled so as to be relative to the average demand from all services. This multiplicative scaling ensures that the mean of the distribution is one. Note that the cumulative distribution function indicates a probability of 52% that the demand is zero.

### 5.3 Correlation

The division of the sample into seven groups permits the correlation between the demands from different services to be explored. The presence of a positive correlation between nearby or similar services would lead to greater variation in the total demand from each group relative to the variation across the whole sample than would be expected if there was no correlation.

The procedure for testing this is closely related to the analysis of variance where a test is carried out for a "random effect" component associated with the groups. The context here is more complicated than usual since the time series aspect imposes serial correlation and the number of services in the sample varied slightly during the study period. The approach was to compute an  $F$  ratio type statistic at each time instant when the flow exceeded 4.3 l/min and to test whether this sequence of  $F$  ratios had mean significantly greater than one, taking into account the serial correlation. The result is an approximation to an idea test, but it clearly showed no evidence for correlation between services.

### 5.4 Demand from Multiple Services

If the correlation or dependence between services is not significant, the demand from more than one service is a simple sum of the demands from one service. The distribution of the demand is found by convolution.

If  $X$  and  $Y$  are random variable with corresponding densities  $f_X$  and  $f_Y$  respectively, then the sum  $Z = X + Y$  has density given by

$$f_Z(z) = \int f_X(x)f_Y(z-x)dx.$$

This convolution can be iterated to generate the distributions of the sum more variables.

### Empirical Density Functions

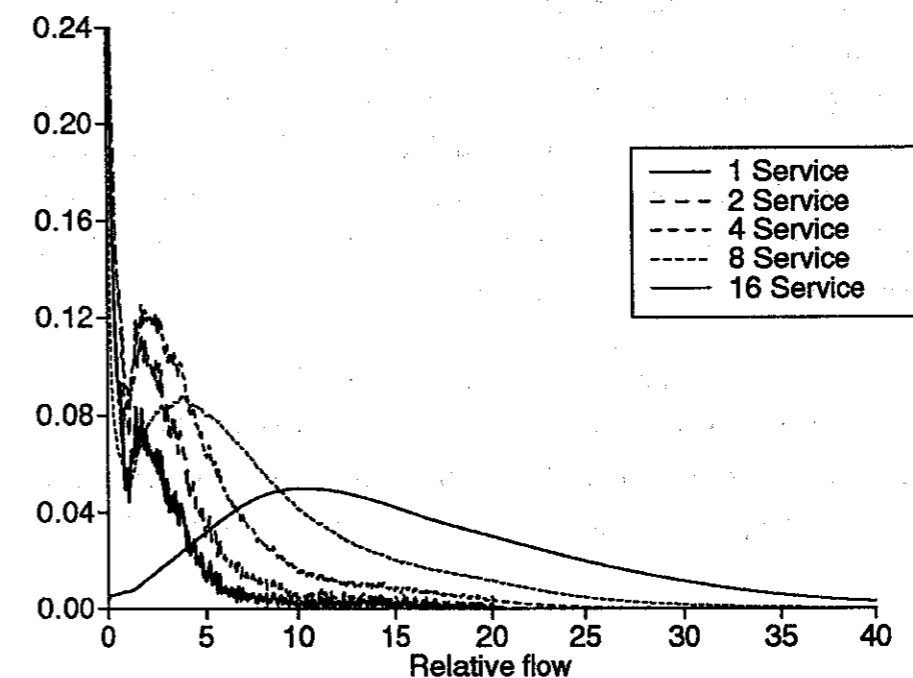


Figure 5.6 : Empirical probability density functions for 1, 2, 4, 8 and 16 services at peak demand. The single service density is derived from Figure 5.5 by smoothing and differentiation. The rest are derived by iterated convolution.

The theoretical procedure above can be replicated with the empirical distribution in Figure 5.5, with the integration being replaced by summation. The most obvious method is to convolve the single service distribution with itself to get the two service distribution, convolving this with itself to get the four service distribution and so on.

The resulting densities are shown in Figure 5.6. Note that the mean value of each distribution equals the number of services.

It is apparent that the skewness which is extreme in the case of the single service distribution is maintained for the multiple service distributions. At relative flow rates close to zero the densities are not particularly smooth but this effect declines as an increasing number of services are considered.

### 5.5 Effect of Bore Ownership and Water Pressure

As a final issue, the effect of bore ownership, the water pressure and whether the service was short or long was examined.

This was explored through regression, with the independent variables being bore ownership (0 = no bore, 1 = bore) and pressure group relative to the "Medium" group. Various methods were used, including regression of the relative flow, regression of the cube root of the relative flow (a common technique with Gamma distributions) and a generalised linear model approach. In all cases the regression explained only a small proportion of the variation (with  $R^2$  values around 0.03 to 0.05). The only statistically significant term was that for bore ownership.

The effect of bore ownership was not measurable and is probably not relevant in setting design specifications since it is not possible to control. The effect of pressure was measurable but below the level of detection due to the small sample of houses that were used. A larger sample of houses may return different results.

## 6. A MODEL FOR DIVERSITY CURVES

### 6.1 The Gamma Distributions

The Gamma family of distributions is defined by probability density function

$$f(x) = \frac{1}{\Gamma(\alpha)} \frac{1}{\beta^\alpha} x^{\alpha-1} \exp^{-\beta x}$$

where  $\alpha > 0$  is termed the shape parameter,  $\beta > 0$  the scale parameter and  $\Gamma(\cdot)$  is the Gamma function. This distribution is termed Gamma( $\alpha, \beta$ ). For further reference see Wilkes, 1962.

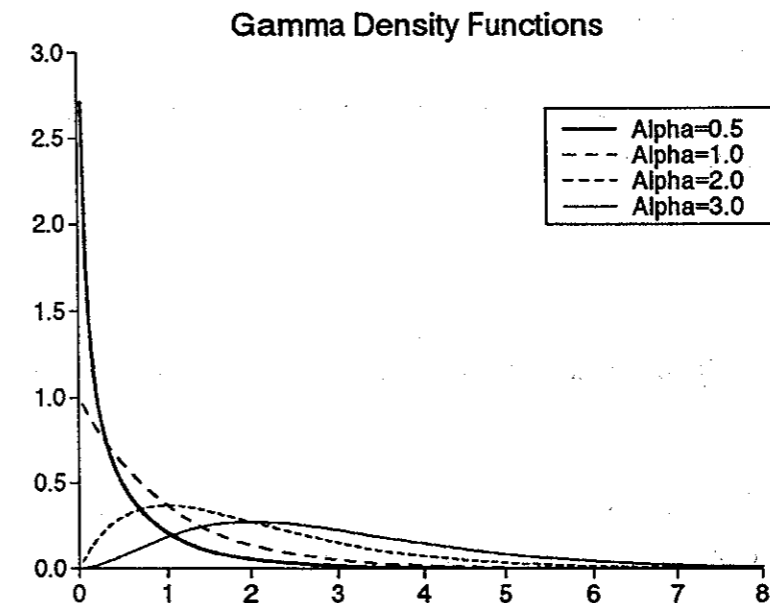


Figure 6.1 : Probability density functions for varying values of  $\alpha$  while keeping  $\beta = 1$ .

The parameter  $\alpha$  gives the family its versatility. When  $\alpha < 1$  the density function has a singularity at the origin while for  $\alpha > 1$  the density is zero at the origin. As  $\alpha$  gets larger the density becomes more symmetrical. This is illustrated in Figure 6.1. For all values of  $\alpha$  the distribution is skewed with a long positive tail.

The mean of the distribution is  $\alpha/\beta$  and the variance is  $\alpha/\beta^2$ . By appropriate choice of  $\alpha$  and  $\beta$  it is possible to fit a wide range of empirical distributions, frequently by matching the mean and variance.

It is important to understand the effect of summing Gamma distributed random variables. Suppose that  $X$  is  $\text{Gamma}(\alpha_1, \beta)$  and  $Y$  is  $\text{Gamma}(\alpha_2, \beta)$ . Then the sum  $X + Y$  has distribution  $\text{Gamma}(\alpha_1 + \alpha_2, \beta)$ . Note that this only occurs when the scale parameters of  $X$  and  $Y$  are the same.

Using this fact, it is possible to construct a simple model for correlated Gamma variables. If  $X = U + V$  and  $Y = U + W$  where  $U, V$  and  $W$  are independent Gamma variables with common scale parameter  $\beta$  and shape parameters  $\alpha_U, \alpha_V$  and  $\alpha_W$  respectively, then  $X$  and  $Y$  are each Gamma (with shape parameters  $\alpha_U + \alpha_V$  and  $\alpha_U + \alpha_W$ ) and correlation  $\frac{\alpha_U}{\sqrt{(\alpha_U + \alpha_V)(\alpha_U + \alpha_W)}}$ . Hence this is a natural model for Gamma variables with positive correlation.

## 6.2 Fitting Gamma Distributions

The distribution of scaled peak demand is guaranteed to have mean one. Hence the variance  $\sigma^2$  is enough to define the distribution since

$$\begin{aligned}\alpha/\beta &= 1 \\ \alpha/\beta^2 &= \sigma^2\end{aligned}$$

is solved by  $\alpha = \beta = 1/\sigma^2$ . The variance for the single service distribution is 5.538 corresponding to  $\alpha = 0.1806$ .

Once the variance of the single service distribution is known and the lack of correlation is accepted, the distribution of total demand from  $s$  services will have shape parameter  $\alpha = 0.1806s$ .

The resulting theoretical distributions are shown in Figure 6.2. This should be compared with Figure 5.6 – the empirical and fitted distributions are extremely close. An example of this is shown in Figure 6.3.

## Gamma Density Functions

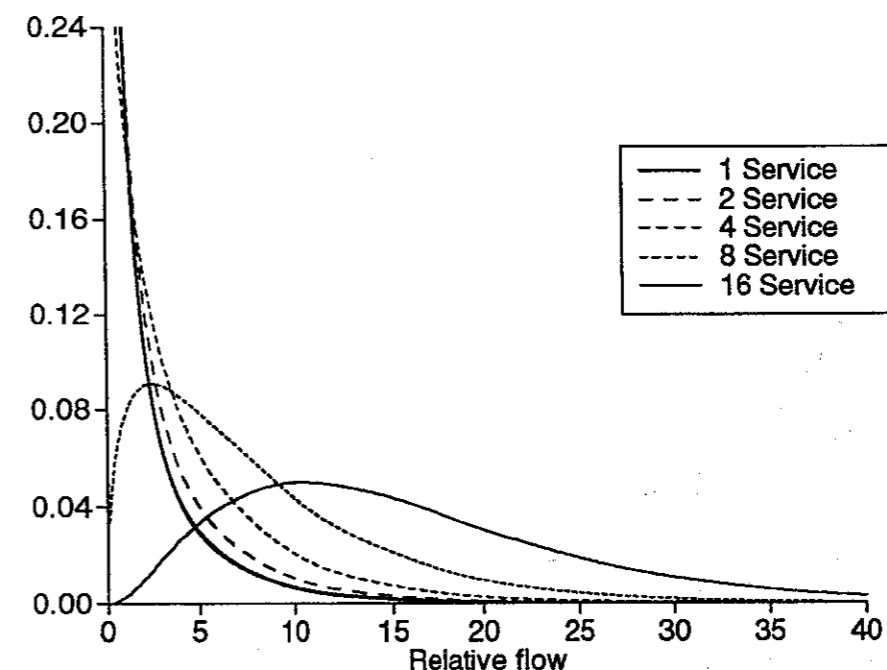


Figure 6.2 : Fitted Gamma probability density functions for 1, 2, 4, 8 and 16 services at peak demand.

## Theoretical and Empirical Densities

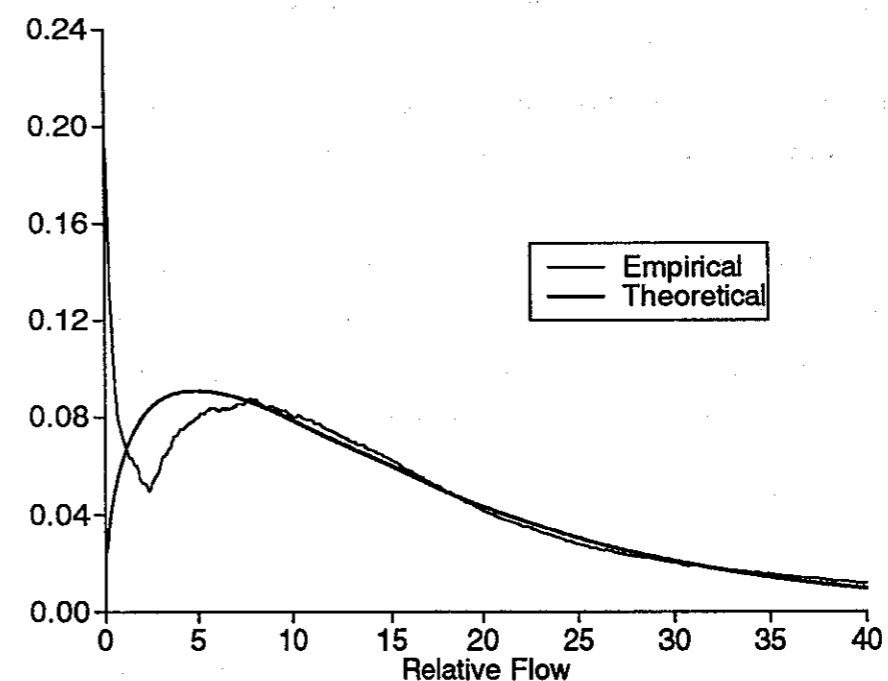


Figure 6.3 : Graph of Theoretical and Empirical distributions for eight services.

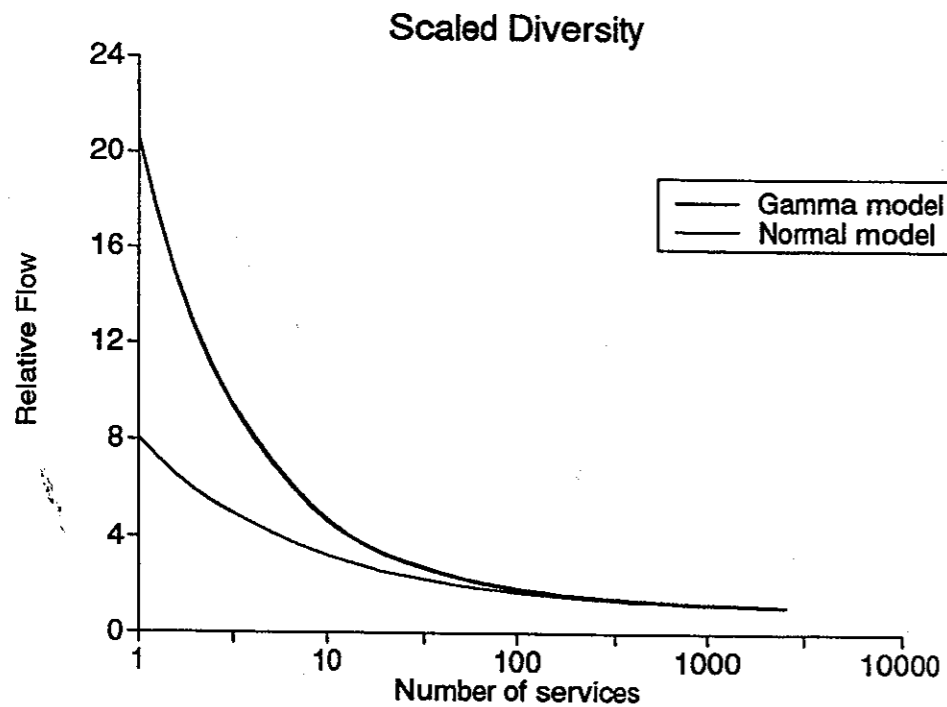


Figure 6.4 : Comparison of the Gamma and normal model diversity curves with the same single service variance.

### 6.3 A Diversity Model based upon Gamma Distributions

The above suggests that it is appropriate to base a diversity curve on the following assumptions:

- The demand from a single service relative to the demand from all services has a Gamma distribution with shape parameter  $\alpha$  and scale parameter  $\beta$ ;
- The correlation between services is not significant ( $\rho = 0$ ); and
- The diversity curve is based upon the upper  $q$  quantile of the distribution.

Note that the current diversity curve based on a normal distribution and the upper three standard deviation point effectively chose  $q = 0.00135$ .

This leads to a diversity curve of the form:

$$\frac{F^{-1}(1 - q, s\alpha, \alpha)}{s}$$

where  $F(., \alpha, \beta)$  is the cumulative distribution function for a Gamma distribution with shape parameter  $\alpha$  and scale parameter  $\beta$ , frequently called the incomplete Gamma function. There is no explicit formula for  $F$  or  $F^{-1}$  so it must be evaluated numerically - standard numerical approximations are readily available.

It is instructive to compare this model with the earlier normal distribution model which gives a diversity curve of the form

$$1 + \frac{\Phi^{-1}(1 - q)\sigma}{\sqrt{s}}$$

where  $\Phi$  is the cumulative normal distribution function. To be comparable so that the variances match we must set  $\alpha = 1/\sigma^2$ . A comparison between the two curves is displayed in Figure 6.4.

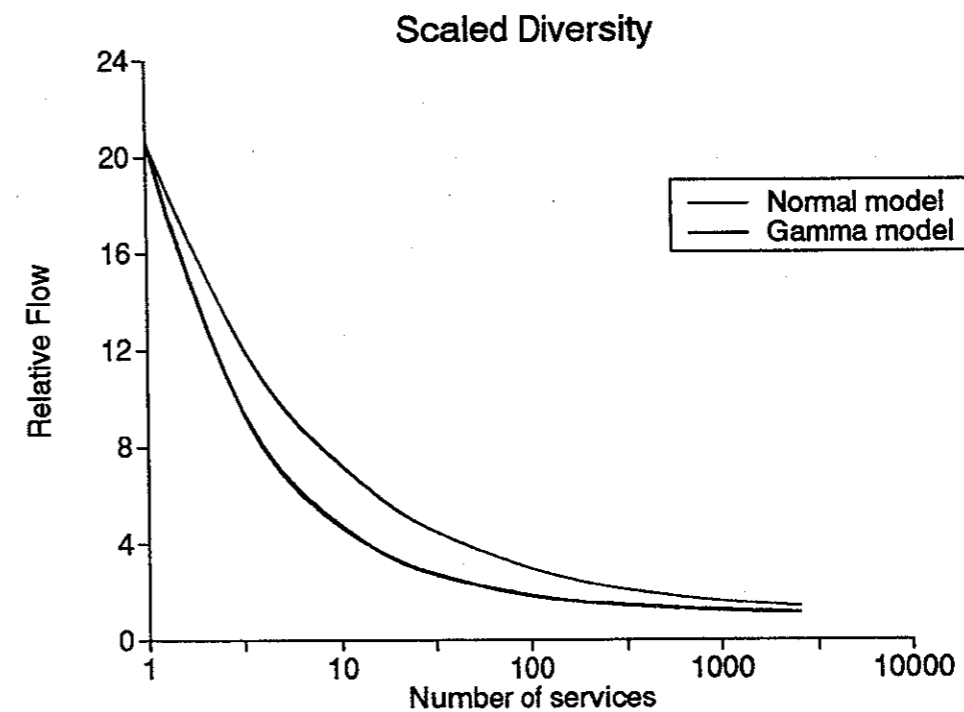


Figure 6.5 : Comparison of the Gamma and normal model diversity curves with the same single service diversity curve value.

However it must be remembered that existing diversity curves were not based upon direct measurement of the single service variance. Rather they were based upon empirical observation of the peak demand from groups of services and then the theoretical normal model curve was fitted by non-linear regression. Hence a more appropriate comparison might be between the curves in Figure 6.5 where the Gamma and normal curves are made to match for a single service. It can be seen that for intermediate numbers of services the Gamma curve is below the normal curve.

Figure 6.5 should be compared with Figure 1.4. The effect on the diversity curve of moving from a normal model to a Gamma model is similar to introducing correlation. This suggests that the earlier work which attempted to directly measure diversity

curves without reference to distributions of demand may have been affected by distribution effects while interpreting them as correlation.

#### 6.4 Conclusions

The Gamma model is based upon a close fit to the empirical demand distribution for a single service. It is mathematically tractable although more work may be required to extend it to situations where services are correlated.

This model suggests a substantially different shaped diversity curve to those in current use (which are based upon the normal distribution). In particular the Gamma diversity curve suggests lower peak demands from intermediate numbers of services. The use of the Gamma curve might thus lead to cost savings in some circumstances.

## 7. RECOMMENDATIONS

Based on these findings the following recommendations can be made.

#### Sampling

In future projects the sampling interval could be increased to three minutes (corresponding to 20 samples per hour) without loss of information. This would result in some savings in data collection and major savings in data management costs.

#### Distributions

The major outcome is the highlighting of demand distributions having a significant effect on the nature of diversity curves.

The substantial proportion of services which have zero demand at the time of system peak demand suggests that the true distribution should include a significant quantum of probability at zero. This would give a mixed distribution - part discrete and part continuous. Such a distribution is mathematically difficult to manage but a Gamma distribution with shape parameter less than one has been shown to be a workable solution. In particular, the Gamma approximation appears to be good in the upper tail which is critical to design procedures.

It is recommended that future investigations of the diversity curve use the Gamma distribution as their basis.

#### Correlation

This study found no evidence of significant correlation between services beyond that imposed by common factors such as weather. In particular, no significant correlation was found between services which were geographically close.

However a survey of this size (84 services) would only have low power in detecting such correlation given the substantial variation in general water demand from one service to the next. It is recommended that this methodology not be used to explore such correlation unless substantially more services can be sampled.

## 8. Acknowledgements

- The study team would like to acknowledge the cooperation of the households in Karawara, Manning, Koondoola, Waterford, Balga, Duncraig, and Hillarys who took part in the experiment.

Without them this project would not have been possible.

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## APPENDIX A – Recruitment of Study Sample and Collection of Household Data

### A.1 The Sample

A total number of eighty-four volunteer households were required for the study. These households needed to fit the following criteria.

- Twenty-eight households were required in each of three water pressure categories: low pressure; medium pressure and high pressure. These categories were defined by the Water Authority of Western Australia (WAWA).
- Within each pressure category, fourteen households were required from a lower socio-economic area and fourteen from a higher socio-economic area (approximately above and below a household income of \$32,000).
- For each group of fourteen volunteer households, eight were required to have short services from the main and six to have long services from the main.
- A maximum of two bore owners were allowed for each service type.

Lower and higher socio-economic areas *which also met the water pressure criteria* were chosen through local knowledge. Households whose incomes were known through surveys from a previous study on water pressure satisfaction were considered for use in this sample. However, they did not meet the definitions for pressure categories which were required in this case.

Therefore, any more accurate sampling by income was impossible as it was decided that potential participants could not be asked their household income at the point of recruitment. It was thought that many people would take offence at the inquiry, considering it an invasion of privacy, thus lessening the success of the recruitment of the sample. An indication of income range could be obtained once a rapport had been established between the field workers and the volunteers.

It was hoped that renting households could be recruited as well as home owners, with the permission of the owners or agents.

## A.2 Recruitment

In the last week of November, 1991, trained CSIRO community field workers recruited the sample of eighty-four volunteer households which met all of the above criteria.

Potential participants were given a letter which explained what was required of them:

- allowing WAWA to install the equipment at their water meters in early December;
- answering a short questionnaire mid December;
- keeping daily records for six weeks showing household water use activities from mid January to the end of February;
- having the equipment removed after March.

They were also given a diagram of the equipment to be installed and notes about the procedure which was provided by WAWA. Copies of the letter and diagrams are shown at the end of this section. They were also informed that they would receive a \$10 gift voucher from a local plant nursery as a token of thanks at the end of the study. No other incentive was offered.

Eighty-three households completed the study. One had to move house unexpectedly in January.

The following shows details of the recruitment of the participant households.

Area	Total Household Contact	Refused	Agreed	Completed Study
<i>Low Pressure</i>				
lower socio-economic	21	7	14	13
higher socio-economic	18	4	14	14
<i>Medium Pressure</i>				
lower socio-economic	20	6	14	14
higher socio-economic	24	10	14	14
<i>High Pressure</i>				
lower socio-economic	19	5	14	14
higher socio-economic	28	14	14	14
Total	130	46	84	83

The major reasons for refusal to participate were 'not interested' (12); 'too busy' (6) and 'poor English' (3).

All participants were provided with an out of hours phone number to use in case of an emergency with their equipment. However, the few households with problems tended to call their particular field workers rather than the emergency number.

## A.3 The Survey

In mid-December, the field workers called back on the participants to conduct the survey. This survey recorded:

- length of time living at that address;
- owning or renting and, if renting, who paid for the excess water consumed;
- how many bathrooms and toilets in the house;
- ownership and details of:
  - dual flush toilets
  - low-flow shower heads
  - instantaneous hot water system
  - washing machine
  - automatic dishwasher
  - spa bath
  - children's wading pool
  - swimming pool
  - bore or use of a bore.
- details of lawn and garden bed reticulation (ie. equipment and regularity etc.);
- number of people in the household (adults, teenagers and children);
- ages of self and partner (if any);
- gross household income range.

### A.3.1 Household Information

#### *Length of Residence*

	N	%
	(84)	
Less than 5 yrs	35	42
More than 5 yrs	49	58

The mean length of residence for those less than 5 years was 2.3 years.

#### *Own or Rent*

	N	%
	(84)	
Own	72	86
Rent	12	14

*If rent, who pays the excess water?*

	N (12)
Self	6
Owner	2
Half Each	2
Don't Know	2

*How many bathrooms?*

	N (84)	%
One	55	65
Two	25	30
Three	4	5

*How many toilets?*

	N (84)	%
One	53	63
Two	26	31
Three	5	6

*Do you own.....*

	N (84)	%
Dual flush toilet/s	25	30
Low flow shower head/s	27	33
Inst. hot water system	23	27
Washing machine	83	99
Aut. dishwasher	20	24
Spa bath	6	7
Wading pool	10	12
Swimming pool	23	27
Bore	10	12

Of the 61 respondents who owned a storage hot water system, 21 knew the capacity (mean = 170 litres). Of the 39 who did not know the capacity, 28 reported having a

large system.

Eight-five percent of respondents reported having an automatic washing machine, ninety-five percent of which were top loading.

Four of the six spa baths were internal. Only six of the ten respondents who owned a wading pool could estimate how often it would be filled each week in summer. The times reported by these people ranged from 'every day' to 'once a fortnight'. Three of the 23 swimming pools were above ground.

Respondents were asked what they used to water their lawns and garden beds and, on average, how often they watered in summer. More than one response was allowed for each question. The following shows the major responses.

*What is used to water lawns?*

	N (84)	%
Manual sprinklers	46	55
Hand water	29	35
Auto. reticulation	24	29
Manual reticulation	8	10
Tap timer	9	11
Travelling sprinkler	3	5
No lawns	4	5
Don't water	3	4

*How often are lawns watered?*

	N (84)	%
Every second day	27	32
Twice a week	18	21
Daily	17	20
Three times a week	9	11
Once a week	4	5
Daily if hot	6	7
Twice a day if hot	4	5

*What is used to water garden beds?*

	N (84)	%
Hand water	45	54
Auto. reticulation	27	32
Hand water pot plants	15	18
Manual sprinkler	14	17
Trickle system	10	12
Tap timer	8	10
Manual reticulation	6	7
If hot, hand water and retic.	3	4
No garden	4	5

*How often are garden beds watered?*

	N (84)	%
Daily	29	35
Every second day	28	33
Twice a week	13	15
Twice a day	5	6
Daily if hot	4	5

*Number of people in household*

No	Total N=84	Adults N=84	Teenagers N=15	Children N=29
1	4	8	9	13
2	23	52	5	10
3	25	13	1	3
4	17	8	0	3
5	9	3	0	0
6	6	0	0	0

*Gross household income*

	N (79)	%
\$0-\$22,000	28	35
\$22,001-\$32,000	19	24
\$32,001+	32	41

*Age of self and spouse/partner (if any)*

	Self N=82	Spouse N=69
15-19 yrs	1	1
20-24 yrs	3	0
25-29 yrs	8	4
30-39 yrs	16	14
40-49 yrs	27	20
50-59 yrs	11	13
60-64 yrs	8	9
65-69 yrs	3	4
70-74 yrs	3	3
75+ yrs	2	1

**A.4 Water Use Records**

Water use record books were designed to complement WAWA's measurements of actual water consumptions. They were to provide a reference for determining what activities may have produced any consumption readings which needed clarification.

The field workers delivered six water use record books to participants a few days prior to the start of this exercise (Sunday January 19, 1992 to Saturday February 29, 1992). Participants were also provided with six, postage paid, addressed envelopes for the return of each record book at the end of each week.

The field workers explained how to fill in the record books. Each contained seven daily record sheets which showed the time of day and major water uses. These required the participants to, generally, just tick a box when any of these activities were conducted. They were also asked to note any other major water use activity which may have occurred but was not included on the sheet (eg. washing the car).

Each weekly book was compiled with a different coloured cover. One participant, on receiving the record books, advised that he would be unable to complete them as he did not have sufficient competency in written English (although he spoke it very well). Of the remainder, only six record books, in total, were not returned over the six week period (ie. 486 out of the 492 were returned). Five of these appeared to have gone astray in the post (three of them from the same area). One participant had misplaced the books and did not report this until the start of the third week. Replacement books were delivered for the remaining four weeks.

A copy of the daily record sheet and instructions are shown at the end of this section.

## A.5 Study Conclusion

- At the end of March, the field workers delivered the plant gift vouchers to the eighty-three households who completed the study.

They also asked a couple of questions to determine if any water use activities had changed during summer with the advent of day-light saving (eg. time of watering of gardens etc.) or any other changes to normal family routine of other years. Most people with timed reticulation had not reset the clock for daylight saving. Apart from a very few households who did most things later in the evening than normal, very little change had occurred.

A copy of this question sheet is also shown at the end of this section.

## INSTRUCTIONS FOR KEEPING WATER USE RECORDS AND AN EXAMPLE OF ONE DAY'S RECORD



Division of Water Resources  
Perth Laboratory  
Underwood Ave, Floreat Park, WA. Postal Address: Private Bag, PO Wembley, WA 6014  
Telephone: (09) 387 0200. Telex: AA 92178. Fax: (09) 387 8211

## HOW TO FILL IN YOUR WATER USE RECORD BOOKS

You have received six water use record books. Each book is for *1 week's record* of your main water use activities - *one day to each page*.

Each day is divided into two Sections

- one for midnight to noon (NIGHT / MORNING)
- one for noon to midnight (AFTERNOON / NIGHT).

Each Section is divided into different times - *mostly periods of 1 hour*; but some longer (eg. Midnight to 6.00am or Noon to 3.00pm).

Down the side of the sheet are various water use activities (eg. washing clothes; showering; outside watering etc.). We would like to know when you do these activities. This way, when the measuring equipment you have at your water meter shows a major water use, we will know what it was.

When you do any of the activities on the sheet, put *a tick in the box* which shows the time you did it. That is, if you wash the clothes at 9.30 in the morning, tick the 9.00 - 10.00 box in the NIGHT / MORNING Section.

**Dishwashing:** You may have a dishwasher but only run it every two days and also wash the pots or other bits and pieces by hand. Tick when you do hand washing of dishes as well as using the dishwasher.

**Shower or Bath:** If more than one person uses the shower or bath in a time period, write the number of people who did so in the appropriate time box.

**Outside Watering:** We have separated Garden-bed reticulation and Lawn reticulation/sprinkler activities. Some people have reticulation which waters lawn and garden-beds at the one time. Therefore, if you have this system, tick both the boxes in the same time period.

**Other major water use:** This is for any other activity which uses more than a small amount of water, such as topping up the swimming pool,

washing the car; hosing down paving etc. If you do any such activity, tick the box for the time and note down the activity at the bottom of the page.

If the things you do span over two time periods, tick both boxes. That is, if the lawn was watered from 7.00pm to 8.30pm, tick both boxes - 7.00 to 8.00 *and* 8.00 to 9.00. If you want to comment on any of your records, please do so in the column marked *Comments* or make any notes at the bottom of the page if this is not enough room.

We have attached an example of a list of activities for a day and the times they were done and how the form would be filled in.

**Do not change the times you normally do any of your the activities.** For example, if you would normally water your lawn in the middle of the day, continue to do so. This measuring study will only work if you go about your normal routine. Some people have already changed normal activity times because of daylight saving. That is OK. Continue to do this. We will discuss what effect daylight saving has had on your routine after the recording period.

We suggest that you keep your Record Book for the week in a handy place with a biro, such as the kitchen bench, and tick the activities as you do them. If you can't do this or forget to do so, please fill in the day's records at the end of the day. *Try not to leave it till the next day as you may find it hard to remember.*

### WHAT TO DO AT THE END OF EACH WEEK

You have been given six 'reply paid' envelopes which fit the Record Books when folded in half. Each Sunday, please put the last week's Record Book in an envelope and post it. There is no need for a stamp.

### WHAT TO DO IF YOU HAVE ANY QUESTIONS OR WORRIES

If you have any questions, please feel free to call me, Blair Nancarrow, or Mary Kelly on the phone numbers on the next page. We will be only too pleased to help as we really appreciate your efforts in this study.

Also, if you have any worries about the measuring equipment or *any aspect of the study at all*, please contact us immediately. We do not mind calls to our homes.

**Contact Phone Numbers:**

**Blair: 387 0290 (work)  
401 9224 (home)**

**Mary: 387 0262 (work)  
342 3446 (home)**

Once again, thank you very much for your participation in the study. It is very important for the future planning of Perth's water resources and the results will also be of use Australia wide.

Blair E. Nancarrow  
Project Co-ordinator

**AN EXAMPLE OF ONE DAY'S WATER USE ACTIVITIES**

**Saturday**

3.00 am	Lawn reticulation came on with timer
9.20 am	Washed the breakfast dishes by hand (no dishwasher)
9.45 - 11.30 am	Did the family clothes washing
1.00 pm	Washed the lunch dishes by hand
3.30 pm	Husband washed the car
3.45 pm	Bathed the two younger children together in 1 bath
4.30 pm	Handwatered the pot plants outside
6.15 - 7.15 pm	Garden-beds watered by reticulation
7.30 pm	Washed the dinner dishes
7.45 pm	Older child showered
9.10 pm	Husband showered
9.45 pm	I showered

Now look at the Record Sheet on the next page to see how it would be filled out.

SATURDAY Jan 25	NIGHT / MORNING				AFTERNOON / NIGHT								Comments (if any)			
	Midnight to 6.00	6.00 7.00	7.00 8.00	8.00 9.00	9.00 10.00	10.00 Noon	Noon 3.00	3.00 4.00	4.00 5.00	5.00 6.00	6.00 7.00	7.00 8.00		8.00 9.00	9.00 10.00	10.00 Midnight
Clothes washing				✓	✓											
Dish washing (by hand)				✓			✓					✓				
Dish washing (machine)																
Shower <sup>1</sup>																
Bath <sup>1</sup>									✓					2		2 children in 1 bath together
Garden/lawn handwater									✓							pot plants
Garden-bed reticulation												✓				
Lawn retic/sprinkler																
Other major water use <sup>2</sup>																

<sup>1</sup> If more than 1 shower or 1 bath in the hour, please write the number (ie. if three people showered between 6.00 and 7.00pm, note 3 in the 6.00 to 7.00pm box instead of ✓.)

<sup>2</sup> A major water use is anything where more than a small amount of water is used (ie. washing the car; topping up the swimming pool; filling a wading pool or children playing with the hose). If you have ticked this item, please note below what the water use was.

..... Washed the car

EXAMPLE

QUESTION SHEET AT  
THE CONCLUSION OF  
THE STUDY



CSIRO  
AUSTRALIA

Division of Water Resources  
Perth Laboratory

Underwood Ave, Floreat Park, WA, Postal Address: Private Bag, PO Wembley, WA 6014  
Telephone: (09) 387 0200. Telex: AA 92178. Fax: (09) 387 8211

Name: .....

Address: .....

Interviewer: .....

### PEAK WATER USE STUDY

I'd like you to think about your daily routine with daylight saving this summer compared with your routine in other summers with no daylight saving. Did you do any of your 'water use' activities at different times of the day this summer?

For example: watering the garden later at night, such as 8.00pm instead of 7.00pm;  
watering the garden first thing in the morning;  
washing clothes in the evenings etc.

YES .... 1                  NO .... 2                  NOT SURE .... 3

If YES or NOT SURE, what?

*Interviewer: Double check that items mentioned were different from other years.  
Ensure you get all the details.*

.....  
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.....  
.....

Is there anything else you did at different times which had nothing to do with daylight saving?

*(Interviewer: Maybe all the children were at school for the first time or maybe someone retired etc. Prompt if little thought given to the question.)*

YES .... 1                  NO .... 2                  NOT SURE .... 3

If YES or NOT SURE, what?

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Are there any other comments you would like to make about the study?

.....  
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.....  
.....  
.....

*Thank the respondent very much for their participation.*

## APPENDIX B – Study Equipment and Data Collection

### B.1 Flow Measurement

The existing 20mm water meter of each property was replaced with a Davies Shephard 20 mm PSM-T Volumetric Cold Water Meter. This meter complies with AS 3556 - Meters for Cold Potable Water. A pulse output facility on the meter provides one pulse per 0.5 Litre of flow.

The pulse output from the meter was coupled to a UNIDATA Model 6003-b logger. The logger was configured to record flow in one minute intervals. A compressed data format was used (Unidata Software) to maximise the use of the 64K logger memory.

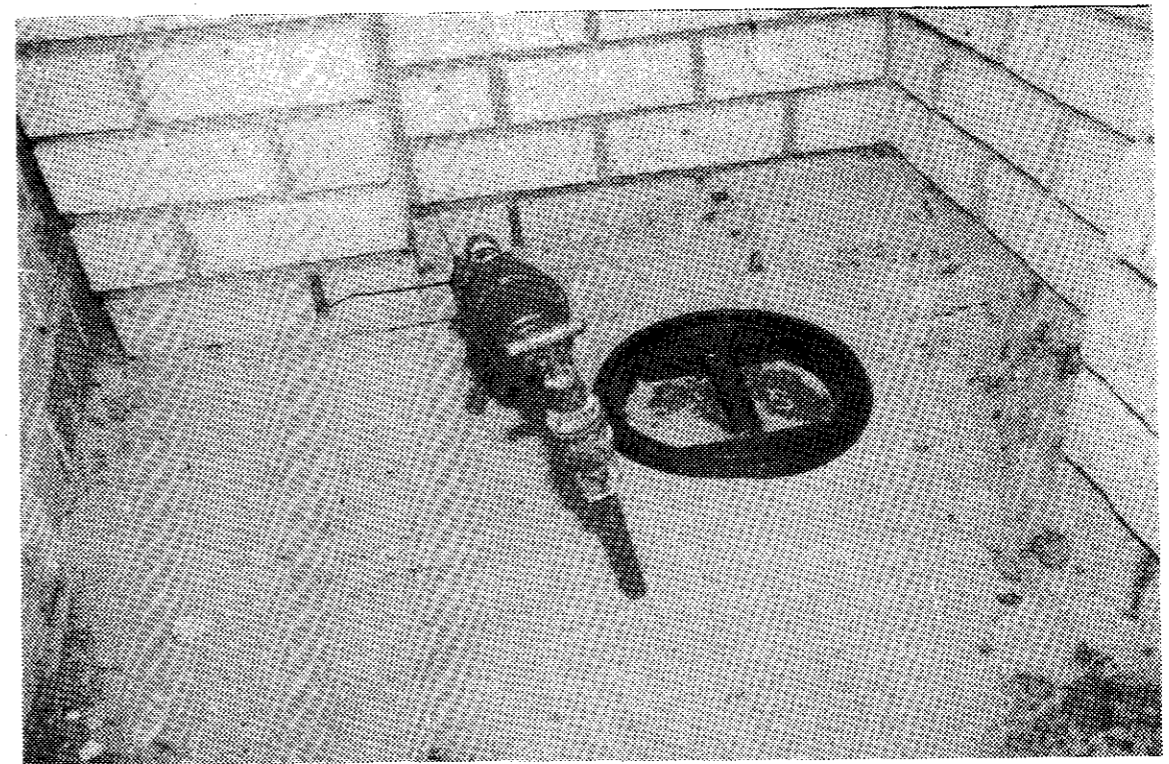
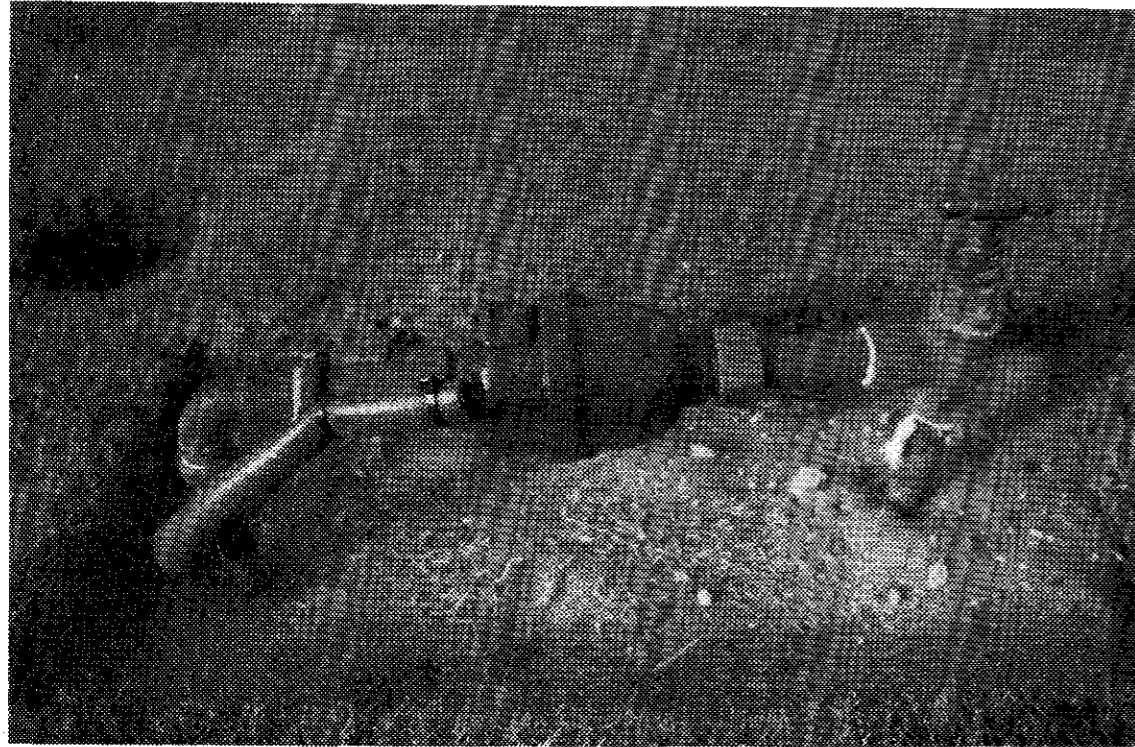
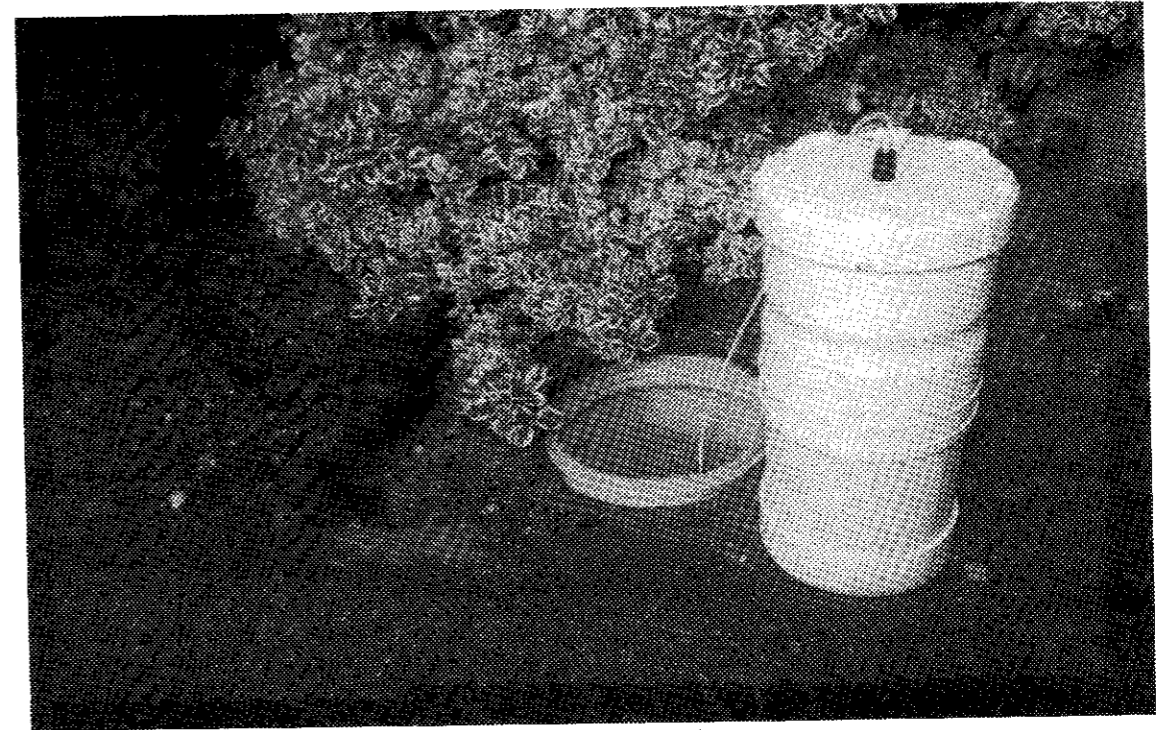


Plate 1 : Flow measurement equipment as installed.

The installed equipment layout is shown in Plates 1 to 4.



**Plate 2 :** Davies Shephard PSM-T 20mm meter with pulse output to logger.



**Plate 3 :** Protective housing for logger located in close proximity to meter.

## B.2 Equipment Monitoring

Each of the 84 households was visited at least fortnightly.

Using a laptop PC and software developed in-house by the Water Authority of Western Australia, each logger was interrogated to determine:

- integrated flow. This was then checked against the dial reading of the 20mm meter.
- the maximum one minute flow
- percentage of logger memory unused
- percentage of battery life remaining

The visit also allowed a visual inspection to ensure equipment was secure and operational.

## B.3 Data Collection

At the completion of the test (or earlier if logger capacity was approaching its limit), the data from each logger was down-loaded onto a NCR 486 PC. The data was manipulated into real time (uncompressed) ASCII format using the HYDSYS software. This data was provided to Data Analysis Australia on disk for evaluation.

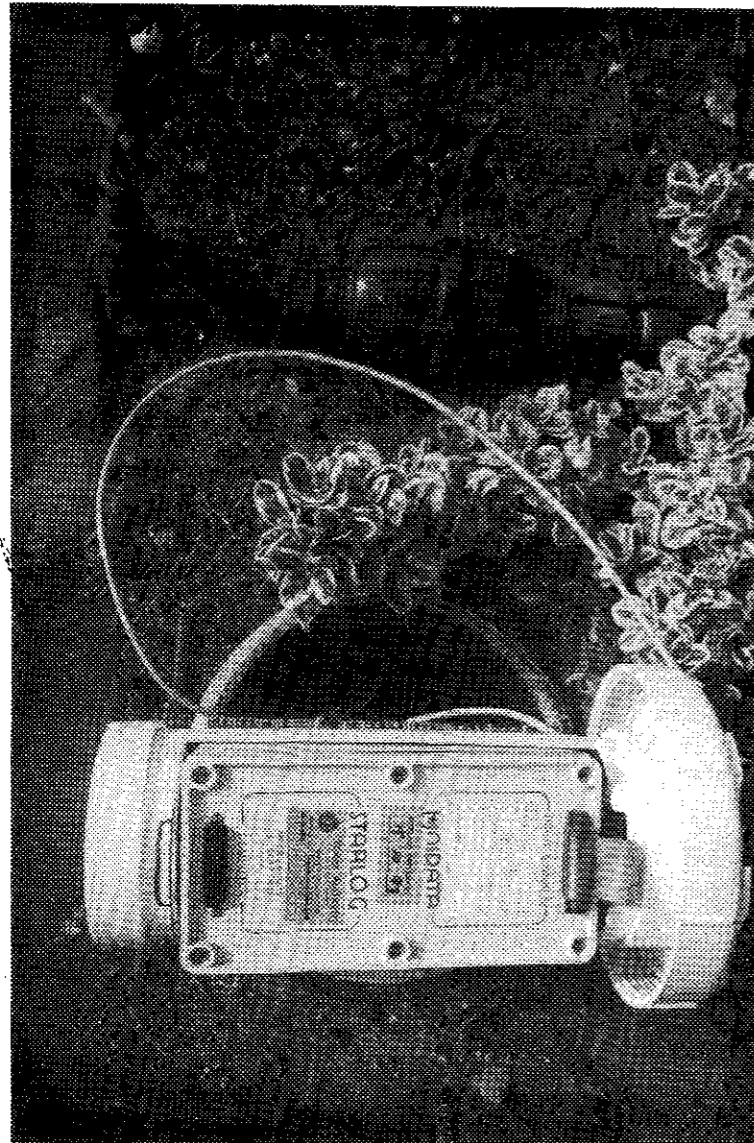


Plate 4 : Unidata Model 60003-b logger.

## UWRAA RESEARCH REPORTS

Report Number	Title	Author	Report Number	Title	Author
1	Trickling filter – solids contact process: Pilot plant studies.	M. Laginestra	21	Management and display of dam surveillance data	D. M. Stirling G. L. Benwell A. B. Murnane
2	A model of water pricing for Melbourne, Sydney and Perth	P. B. Dixon P. M. Norman	22	Evaluation and demonstration facilities for primary sensors	J. A. Lanaway M. Cavey
3	Taste generation associated with chloramination	M. Kerslake	23	Modelling and design of reservoir aeration destratification systems	D. P. Lewis J. C. Patterson J. Imberger R. P. Wright S. G. Schadlow
4	Bacterial regrowth in water supplies	K. Power L. A. Nagy	24	Modelling optimum conditions for reservoir destratification using mechanical mixers	R. M. A. Velzeboer J. A. Cugley J. C. Patterson
5	Leakage management: Assessing the effect of pressure reduction on losses from water distribution systems	B. Horvath	25	Methods for detection of <i>Giardia</i> and <i>Cryptosporidium</i> in water: A preliminary assessment	C. A. Bee P. E. Chrsty B. E. Robinson
6	Improving communication with the public on water industry policy issues	B. E. Nancarrow G. J. Syme	26	Toxic cyanobacteria in water supplies: Analytical techniques	D. J. Flett B. C. Nicholson
7	Water use efficiency of domestic appliances	I. J. Beith D. J. Horton	27	Tracing toxic discharges to sewers by analysis of biofilms	D. Oliver T. Watson
8	Pilot plant study of fermentation units to increase degradable COD fraction in sewage.	P. J. Bliss D. Barnes P. R. Evans I. Law	28	Electronic meter reading: Link between water meter and house	P. J. Reid J. S. Renwick M. F. Prior
9	Artificial destratification of water storages in Australia.	T. F. McAuliffe R. S. Rosich	29	Identification of common noxious cyanobacteria: Part 1 – Nostocales	P. Baker
10	Taste thresholds of mono-chloramine and chlorine in water	R. O'Halloran C. Veres	30	Forecasting water demand using weather data	M. N. Viswanathan
11	Chromatographic analysis of chloramines using electro-chemical detection	R. O'Halloran Hai Lin Ge P. Spizziri	31	Effects of controls on water consumption	M. N. Viswanathan
12	Glass reinforced plastic bore casing for large diameter and deep bores	R. Bowyer	32	Biological removal of iron from groundwater: Preliminary studies	M. N. Viswanathan
13	A guide to improving communication with the public on water industry policy issues	B. E. Nancarrow G. J. Syme	33	Statistical modelling of water main failures	E. Tsui G. Judd
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15	Chloramination of Water Supplies	P. M. Thomas (ed)	35	Performance auditing in the Australian urban water industry	S. O'Kane I. Parry D. Blunden D. Herring
16	The 1988 Australian Winter Storms Experiment: Report on aircraft observations	J. B. Jensen	36	Microbiological studies on enhanced removal of phosphates from sewage	R. C. Bayly J. W. May G. Vasiladis G. N. Rees
17	Pipeline assets: Life cycle economic life	R. Vass management and M. Anderson R. Lewis D. Samson	37	Magnetite and microwaves in sewage effluent treatment	D. R. Dixon A. J. Ware
18	Development of empirical model for tradewaste discharges to small treatment plants	Camp Scott Furphy	38	Polymer based electrode for the selective detection of dichloramine	Y. Lin G. G. Wallace
19	PRELIM users guide (Amended): Australian Version	Camp Scott Furphy	39	Current cost asset valuation: Methodology	J. Dyke
20	Chemical regeneration of activated carbon: Preliminary studies	G. Newcombe			

## UWRAA RESEARCH REPORTS

Report Number	Title	Author	Report Number	Title	Author
40	Community analysis of household water pressure satisfaction	G. J. Syme B. E. Nancarrow B. J. Bishop P. VanderWal	59	Electronic household water meter: Investigation into a cost effective design	Z. Balazic A. Leong
41	Assessment of coagulants for water treatment	C. Donati	60	Domestic greywater reuse: Preliminary evaluation	B. Jeppesen
42	Coagulants for water treatment: A generic guide	ACWQR	61	Chemical regeneration of activated carbon: A feasibility study	G. Newcombe
43	Optimal prices for urban water: A general equilibrium model applied to Melbourne	P.B. Dixon D.J. Baker	62	Tracing toxic discharges to sewers by analysis of biofilms (Stage 2)	W. H. Lock
44	Applications of the Streaming Current Detector in water treatment	W. Barron D. R. Dixon M. Pascoe	63	Production of Jerusalem artichoke hybrids under irrigation using urban wastewater	M. Parameswaran
45	Sydney coastal stormwater study	W. G. Rowlands et.al.	64	Control of pitting corrosion of copper tubes in potable waters	R. J. Taylor P. H. Cannington
46	Identification of common noxious cyanobacteria: Part 2 - Chroococcales and Oscillatoriales	P. Baker	65	Measurement of Total Factor Productivity in major water utilities: Melbourne case study	I. Manning E. Molyneux
47	Levelling using the Global Positioning System	A. P. Armstrong P. A. Collier F. J. Leahy	66	Assimilable organic carbon as a measure of bacterial growth potential in water supplies	K. C. Tapang M. Drikas L. E. Bennett
48	Allocation of sewerage costs to customer segments	R. Hood P. Geary	67	Simultaneous peak water demands in residential areas	J. Henstridge G. J. Syme B. E. Nancarrow
49	Impact of urban lawns on nutrient contamination of an unconfined aquifer	M. L. Sharma D. E. Herne P. G. Kin J. D. M. Byrne			
50	Early warning system for hazardous substances in sewage	R. O'Halloran B. A. Sexton N. H. Pilkington			
51	Management model for trade waste discharges to small treatment plants (including PRELIM VERSION 4.0 Users Guide)	Camp Scott Furphy			
52	Automatic meter reading: Link between meters and billing centre (Combined utilities trial)	B. Phey A. Leong Z. Balazic			
53	Prediction of perceived odour strength and type from composition of sewage odour mixtures	D. G. Laing A. Eddy D. J. Best			
54	Tracer studies using bacteriophage to predict the fate of viruses in the marine community: Preliminary assessments	B. J. Richardson A. L. Charlton S. Currie P. Ashton I. Lowther			
55	Development of a water quality analyser suitable for unattended use in rivers and streams	G. W. Skyring I. A. Johns J. A. Cugley			
56	Enhancement of nitrification in wastewater lagoons	P. M. Gross			
57	Identification of critical water supply assets	PPK Consultants			
58	Water in Our Environment: Education Project	H. Breidahl D. Cliffe H. Henderson			

