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Severity-frequency-duration measures for urban water supply systems

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Abstract

Urban water supply authorities are required to supply water to their customers (both bulk water customers and small users) with a certain level of reliability. Various indicators have been used in the past to measure the reliability of supply to these customers and mostly they are related to water restrictions. They include supply reliability, severity of restrictions and duration of restrictions. These measures in the past have not addressed the issue of frequency of meeting or violating these measures, although it is understood that this additional information would help the water supply planners and customers (especially the large bulk water users) in planning and managing their water supply and demand. This issue was addressed in this paper by deriving severity-frequency-duration (SFD) curves for use in management of urban water supply systems. A methodology, which uses water supply system simulation and partial duration series analysis, was developed to derive the SFD curves. The methodology was applied to a hypothetical two-reservoir system supplying water to a demand centre with typical urban restriction and other operating rules. The results showed that it was possible to derive a consistent set of SFD curves, which provided information on frequency of restrictions with different durations and severities.

INTRODUCTION

Water supply authorities use reservoir storage systems to supply water demand of their customers. The reservoir storage systems are necessary, since the required diversion rate cannot be supplied with natural river flow at certain times of the year. This is especially true for rivers and streams with a high degree of variability. These reservoir systems are designed to supply the design demand subject to certain reliability conditions, which allow for magnitude and variability of river flows (McMahon and Mein, 1986, p1).

In recent times, a significant shift has emerged throughout the world from construction of water resource projects to efficient operation and management of existing systems to meet the ever-increasing demand. The reasons for this shift include the non-availability of water resources for further development, the limited availability of funds for capital works and the spirited and justifiable lobbying of environmental groups against the construction of major water resource projects. However, as part of these new water resource management frameworks, the water supply authorities are required to supply water to their customers with a certain level of reliability. Therefore, the water supply is associated with a certain level of security. The customers can be large bulk water users such as irrigator groups and urban water retail companies, or individual small users such as small industries and households. Various indicators have been used in the past to measure the security of supply to these customers and mostly they were related to how the demand has been supplied or restricted. Most urban water authorities in Australia (e.g. Melbourne Water) use supply reliability, severity of restrictions and duration of restrictions as these indicators (Perera and Kularathna, 1998; Perera et al., 1999; Yurisich and Rhodes, 1999). However, these indicators do not address the issue of frequency of meeting or violating the level of security, that is, how often these different security criteria were met or violated, although it is appreciated that this additional information would help the water supply planners and customers (especially the large bulk water users) in managing their water supply and demand.

This paper addresses the research conducted on this issue. The severity-frequency-duration (SFD) curves were developed for urban water supply systems, which showed the frequency of restrictions of various magnitudes and durations. Similar curves have been produced for low flow analysis and rainfall analysis. Low flow analysis yields low flow frequency (LFF) curves, which provide a relationship describing the frequencies of occurrence of low flows of different magnitudes over different low flow durations. The rainfall analysis produces Intensity-Frequency-Duration (IFD) curves for estimating design flood hydrographs, which defines a relationship describing the frequency of storm events of different storm durations and different intensities. All these curves (i.e. SFD, LFF and IFD) are different to flood frequency curves, which define the frequency of floods of different magnitudes; peak flood discharge is of more concern than the duration of flood in classical flood analysis.

The methodology used for this study for deriving SFD curves is described first. A case study is described then finally, the conclusions drawn from the study are presented.

METHODOLOGY ADOPTED

The methodology adopted consisted of two separate stages. The first stage used a water supply simulation model to study the behaviour of the water supply system under its operating rules. The results of the simulation model in relation to supplying demand and restrictions were then noted. As the second stage, a partial duration series analysis of the results of restrictions obtained from the simulation model was conducted to develop the SFD curves.

WATER SUPPLY SIMULATION MODEL

The REsource ALlocation Model - REALM (Diment, 1991; Perera and James, 1999, 2000) was used to analyse the water supply system considering its streamflows, demands and system details including operating rules. REALM was used in this study, since it is widely used in three states of Australia, namely Victoria, South Australia and Western Australia, for planning and management of both urban and irrigation water supply systems. The simulation was conducted for a typical planning period of the water supply system using a monthly time step. Monthly time steps are generally used for most water supply planning studies. Since SFD curves were developed using results related to water supply restrictions, the urban restriction rules used in REALM are briefly described below. Most urban water supply authorities in Australia (Sheedy and Kesari, 1988; Yurisich and Rhodes, 1999) use this type of urban restriction rules.

Urban restriction rules

Water restrictions are imposed when the system storage volume is low during drought periods, to ensure that supply can be maintained for essential uses throughout the dry spell. The restriction rules set the timing for imposing restrictions and the degree of severity of such restrictions. Typical restriction rule curves used for urban water supply systems are shown in Figure 1, in which AAD refers to the Average Annual Demand. When the total storage level at a particular month is above the values defined by the upper rule curve, no restrictions are imposed on the water demand. If the storage volume is below the values defined by the lower rule curve, the water demand is restricted to the base demand, which is generally the in-house demand. If the storage volume is in an intermediate zone, the demand is then restricted by the appropriate estimated percentage reduction; in this case only the demand above the base demand is restricted. As the total storage volume falls, more severe restrictions are progressively imposed. Similarly, when the storage recovers, restrictions are eased.

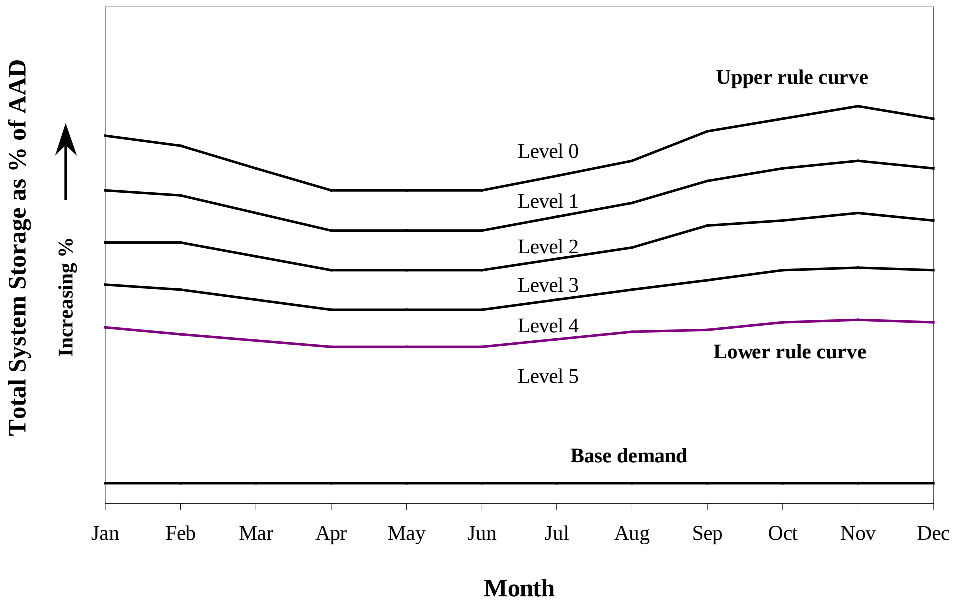

Figure 1. Typical Urban Restriction Rule Curves.

Figure 1 shows a 4-stage restriction policy, which defines 4 intermediate restriction zones between upper and lower rule curves. Each zone is associated with its restriction level defined by integer values (in this case between 0-5). A 4-stage restriction policy is used in the case study in this paper.

Output from simulation

Among other detail outputs, REALM produces a time series of restriction levels (indicating severity) experienced during the planning period. This time series is used in the frequency analysis, which is described below.

PARTIAL DURATION SERIES ANALYSIS

Analysis of frequency of severity of restrictions used in this study was similar to the classical low flow frequency analysis. As stated in McMahon and Mein (1986, p 62), two types of low flow frequency analyses have been used in the past, namely the annual series and the partial duration series. The former was based on the minimum flow of certain durations (usually less than 183 days) in each year of record, while the latter usually considered low flow events with duration greater than 12 months. The partial duration series approach was used in this study, since the water resource planners are interested in the frequency of consecutive restrictions lasting more than 12 months, in addition to low duration events.

The time series of restrictions levels (obtained from the simulation of the water supply system) contains several independent restriction events. Independent events were considered as events at least one month apart. That is, there should be at least one-month gap free of restrictions between two restriction events. The restriction levels within these independent events were analysed to produce the SFD curves. The procedure used to derive the SFD curves for restrictions of *n*-month consecutive duration is described below.

For each independent restriction event, most severe *n*-month consecutive restrictions were extracted, and the restriction levels were averaged to produce an average severity over the duration. These severities were then ranked in order to compute the plotting positions. As stated in McMahon and Mein (1986, p 66) and Laurenson (1987), for partial series analysis of this kind where the duration of the events exceeds one year, plotting positions should be computed in terms of the recurrence interval. The generalised plotting position equation, which is less biased (McMahon and Mein, 1986, p 66), can be used for this purpose. It is given in Equation (1).

$$T = \frac{N - 2c + 1}{M - c} \qquad (1)$$

where

T is the sample recurrence interval and equals the mean interval between events equal to or less than the *n*-month restrictions of certain average severity.

M is the rank of the event with a certain average severity (already selected); the highest severity event given the rank of 1.

N is the number of years considered in the analysis.

c is a constant, which depends on the theoretical distribution to be used in frequency analysis in fitting data. If a single value is required to be used for all distributions or if the applicable distribution is unknown, Cunnane (1978) recommended the best value of *c* as 0.4. Laurenson (1987) re-iterated that the use of $c = 0.4$ leads to an unbiased estimate of the population standard deviation.

Although Equation (1) is the general plotting position equation, it has to be modified to reflect the average recurrence interval of *n*-month events. The modified equation is given in Equation (2). The reader is referred to McMahon and Mein (1986, pp 66-67) for details of this modification. Equation (2) with $c = 0.4$ was used in this study.

$$T = \frac{N - \frac{n}{12}(2c - 1)}{M - c} \qquad (2)$$

A common approach used in the past for partial series analysis is to plot data with respect to their plotting positions [e.g. Equation (2)] to any scale that linearised the relation. Commonly used scales are natural, semi-log, log-log, semi-probability and log-probability. Use of these scales in partial series analysis can be found in Stall and Neill (1961), McMahon and Mein (1986, p 68) and Laurenson (1987). A similar analysis is used in this paper.

CASE STUDY

System and Data

A hypothetical example of a two-reservoir system is considered in this paper to illustrate the methodology described earlier in deriving SFD curves. This example has also been used in the REALM Getting Started Manual (Victoria University of Technology and Department of Natural Resources and Environment, 2000). Basic system, streamflow and demand data given in this manual were used for the case study.

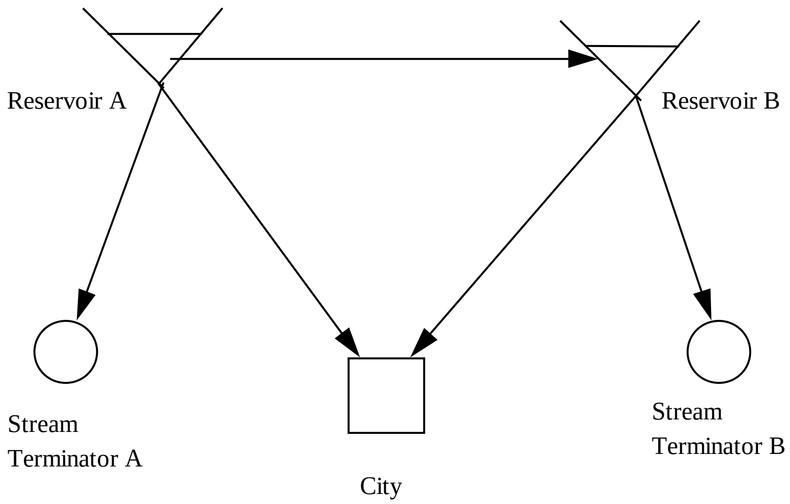

Figure 2. Schematic Diagram of Urban Water Supply System.

Reservoirs A and B supply water to a City. Both reservoirs receive streamflow from their own catchments. Reservoir A can transfer water to reservoir B. The maximum storage capacities of reservoirs A and B are 100,000 and 60,000 Ml respectively. The minimum capacities for both reservoirs are considered to be zero. The evaporation loss in reservoir A is modelled, but not in B. Water is supplied to the City through pipes. The interstorage flow depends on the storage volumes of both reservoirs A and B, and it is managed in such a way that the reservoir storage volumes tend to be proportional to their respective storage capacities. Excess water from reservoirs is spilled via the original river course. The schematic diagram of the water supply system is shown in Figure 2.

Table 1. Restriction Policies Used.

Month	Base Demand	Policy 1 (% AAD)		Policy 2 (% AAD)	
	(% AAD)	Upper Curve	Lower Curve	Upper Curve	Lower Curve
Jan	6	130	70	120	60
Feb	6	120	60	110	50
Mar	6	110	50	100	40
Apr	6	100	45	90	35
May	6	90	40	80	30
Jun	6	90	40	80	30
Jul	6	90	40	80	30
Aug	6	90	40	80	30
Sep	6	100	45	90	35
Oct	6	110	50	100	40
Nov	6	120	60	110	50
Dec	6	130	70	120	60

Table 2. Amount Restrictable for Different Restriction Levels.

Level	Relative Position	Amount Restrictable
0	0	0
1	25	20
2	40	40
3	60	60
4	80	80

The streamflow data at the reservoirs and climatic data (for modeling reservoir evaporation in reservoir A) were available for use in the simulation model for a period of 28 years. The total mean annual flow (MAF) at the two reservoirs was approximately 104,000 Ml. A constant annual demand of 87000 Ml (which is approximately 84% of MAF) was considered with monthly demand disaggregation factors to reflect typical high demands during summer months and low demands during winter months. Two different 4-stage urban restriction policies were considered to investigate the effect of different restriction policies on SFD curves. However, the amount of restrictable demands corresponding to various restriction levels were the same in both cases. These restriction details are shown in Tables 1 and 2. They reflect the typical urban restriction policy shown in Figure 1. Policy 2 consists of curves 10% AAD less than those of Policy 1, and therefore it is comparatively a riskier policy. The relative position of Table 2 defines various intermediate restriction curves in relation to upper and lower rule curves.

REALM was used to study the performance of the water supply system under above data on streamflow, demand, system details and operating rules, considering both forms of restriction rules (i.e. policies 1 and 2 of Table 1). The restriction levels were then noted for the planning period for the two cases. A partial series analysis was then used to derive the SFD curves for various consecutive duration of restrictions. The durations of 3, 6, 9, 12, 18 and 24 months were considered. Of natural, semi-log, log-log, semi-probability and log-probability, it was found that the semi-probability (i.e. severity on natural scale and recurrence interval on probability scale) plot linearised the partial duration series plot for all durations better than the others, and therefore, was used for the case study.

Figure 3 shows the frequency of 3-, 9- and 18-month consecutive restrictions with varying levels of average severities over the duration for the case of restriction policy 1. A linear regression line was plotted for each duration. For larger durations, points seem to generate a good linear plot compared to 3-month duration. For 3-month duration, there were more restriction events and they tend to produce almost the same average severity, which is usually the case. Therefore, the linear relation for 3-month duration restrictions was not as good as for the other durations, which is to be expected.

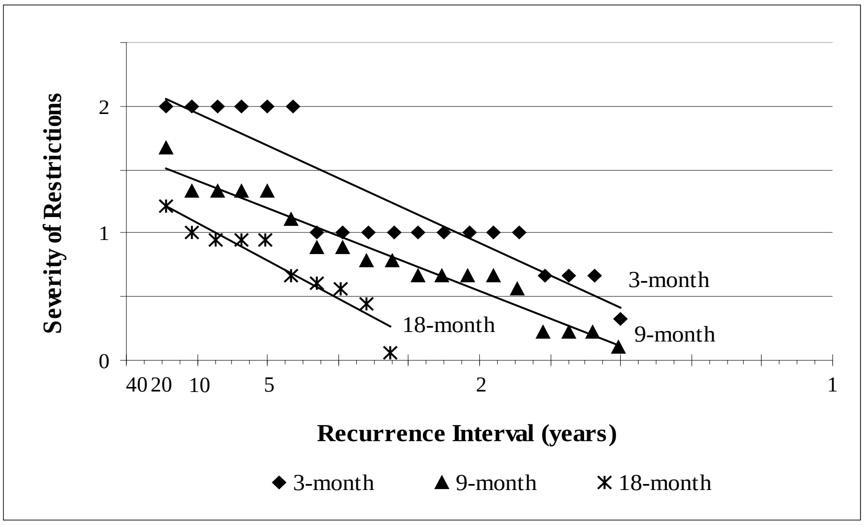

Figure 3. SFD Curve Fit for Restriction Policy 1.

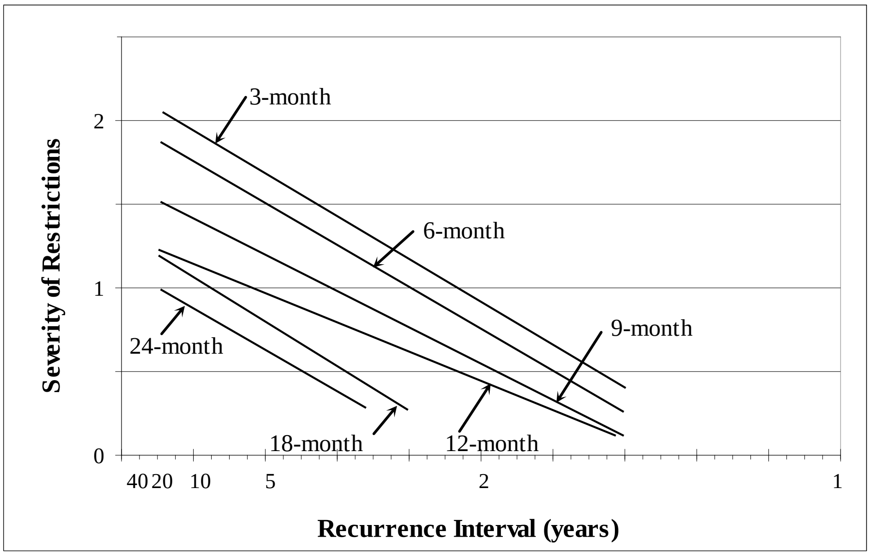

Figure 4. SFD Curves for Restriction Policy 1.

The SFD curves (i.e. regression lines of Figure 3) for all durations are plotted in Figure 4 for restriction policy 1. The trend in Figures 3 and 4 shows that for a given duration, as the average severity over the duration increases, the frequency decreases, which is to be expected. Similarly, for a given frequency of restriction events (e.g. recurrence interval of 1 in 5 years), the longer duration restrictions will have lesser average severity than for shorter duration restrictions. Also, for a given average severity over the duration of restrictions, there is a higher frequency for low duration restrictions to occur compared to longer duration restrictions.

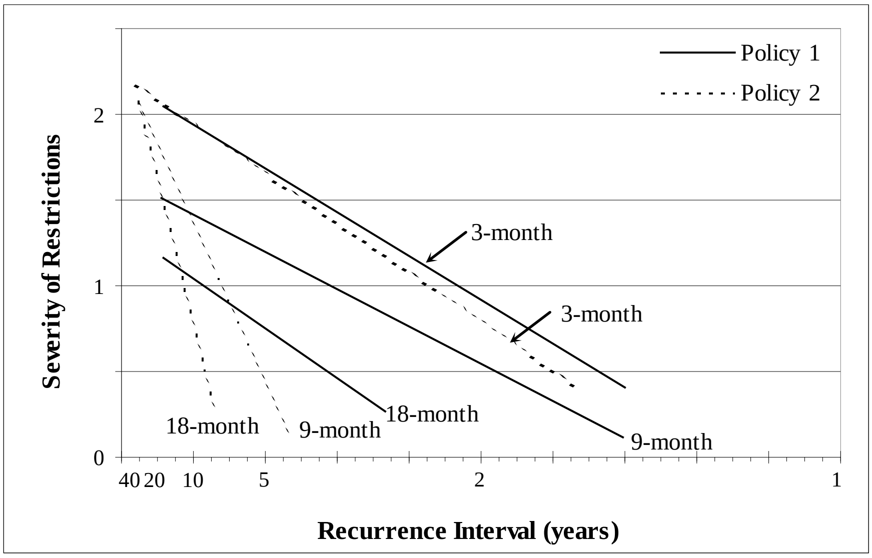

Figure 5. Comparison of SFD Curves for Policies 1 and 2.

Figure 5 shows the SFD curves corresponding restriction policies 1 and 2. As stated earlier, policy 2 is relatively riskier compared to policy 1. The policy 2 delays the imposition of restrictions, which in general may result in more severe restrictions, when restrictions are imposed. However, this is not seen in Figure 5. The reason for this is the complex interactions of the storage volume and the restriction rules. The storage volume at the start of the simulation time step triggers the restrictions and these restrictions later determine the storage volume at the end of the time step, which becomes the storage volume at the beginning of the next time step (i.e. one drives the other). For example, when restrictions are triggered with policy 2, the restrictions may start with a severe restriction level than with policy 1, but bounce back quickly because of higher demand reductions. Therefore, in comparing different restriction rules, it is necessary to look at indicators such as storage behaviour, recoverability of storage after restrictions etc., in addition information on SFD curves. These indices depend on streamflow, demand and system characteristics.

The SFD curves in Figure 5 are almost the same for both policies for restrictions of 3-month duration. For larger durations, severity of events of different frequencies shows relatively a minor change with a conservative restriction policy, while it is fairly dramatic for the riskier policy. However, for riskier policies, the average severity over the duration is lower at low recurrence intervals compared to conservative policies, and vice versa for higher recurrence intervals. These again may be a function of the system, streamflow and demand data, and the level of 'stress' of the system ('stress' is defined by the ratio of annual demand to MAF; higher the ratio, the 'stress' is high). Therefore, the effect of restriction policies on system behaviour and SFD curves needs to be investigated further with additional performance measures.

SUMMARY, CONCLUSIONS AND FUTURE WORK

A methodology, which uses simulation of water supply systems and partial duration series analyses of restriction levels, was developed to produce severity-frequency-duration (SFD) curves for planning of urban water supply systems. These curves provide information on the frequency of restrictions of various consecutive durations and severities, which are useful for water supply planners and managers. A case study of a hypothetical 2-reservoir water supply system demonstrated the methodology and produced realistic SFD curves.

Following general conclusions were made based on the results of the case study. For both frequent and infrequent restriction events, the severity of longer duration restrictions is lesser compared to shorter duration restrictions, and vice versa. Risky restriction policies, which triggers restrictions later than a normal policy provide less severity for frequent restriction events, but provide higher severity for infrequent events. The rate of change of severity from frequent events to infrequent events for these riskier policies is extremely high. However, it should be noted that the SFD curves and the conclusions drawn from this study depend on streamflow, demand and system characteristics including operating rules. They also depend on the level of 'stress' of the system.

SFD curves in this study considered only one streamflow data sequence, which is assumed to occur during the planning period. However, this will not occur during the planning period and therefore, it is necessary to consider equally likely streamflow scenarios in deriving SFD curves. This can be done with stochastically generated streamflow data sequences. Furthermore, a detail study is proposed to investigate the effect of different restriction policies on the bahaviour of urban water supply systems, using several relevant performance indicators. To this end, it may be necessary to include other performance indicators such as storage recoverability, robustness, vulnerability, supply reliability etc., in addition to SFD curves. The level of 'stress' of the system may also have to be included in such a study. These issues are identified as future studies.

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