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WATER SUPPLY RISK ASSESSMENTS USING STOCHASTIC PEAKING FACTORS

A method for sizing back-up provisions to match probable water supply failures

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ABSTRACT

The availability of stochastic peaking factors allows water supply system risk assessments to be undertaken applying a methodology based on the binomial probability distribution. The methodology determines the backup provision needed for a probable failure event while retaining the same level of service adopted for the supply system for normal operational conditions.

Key Words: Water supply; Peaking factor; Stochastic; Risk; Level of service.

INTRODUCTION

The companion paper, *Water Supply Peaking Factor Stochastics*, L. Donaldson (2018), outlines the preparation of the 100, 50, 20, 10, 5, 2 and 1-year recurrence interval Maximum Day (MD) and 30 Day peaking factors for the south east Queensland supply area with average day demands between 0.1 and 600 ML/d. Figures 1 and 2, and Tables 1 and 2 illustrate and list the so determined MD and 30 Day peaking factors.

Table 1: Maximum Day Peaking Factors

RI	Supply Area Demand (*ML/d*)												
(*Year*)	0.1	0.3	0.5	0.7	0.9	1.4	2.7	6.1	14.4	35	74	192	597
1	1.80	1.50	1.44	1.39	1.35	1.35	1.35	1.42	1.45	1.43	1.42	1.39	1.38
2	2.50	1.90	1.76	1.69	1.62	1.60	1.57	1.62	1.63	1.57	1.54	1.48	1.45
5	3.86	2.60	2.29	2.17	2.07	2.01	1.91	1.92	1.89	1.79	1.71	1.62	1.54
10	5.37	3.29	2.80	2.64	2.49	2.38	2.22	2.18	2.12	1.96	1.85	1.73	1.62
20	7.46	4.16	3.42	3.20	3.00	2.82	2.58	2.48	2.38	2.16	2.00	1.85	1.70
50	11.52	5.69	4.46	4.12	3.82	3.54	3.14	2.94	2.76	2.45	2.22	2.01	1.81
100	16.00	7.20	5.45	5.00	4.60	4.20	3.65	3.35	3.10	2.70	2.40	2.15	1.90

Figure 1: Maximum Day Peaking Factor Exceedance Probability Profiles

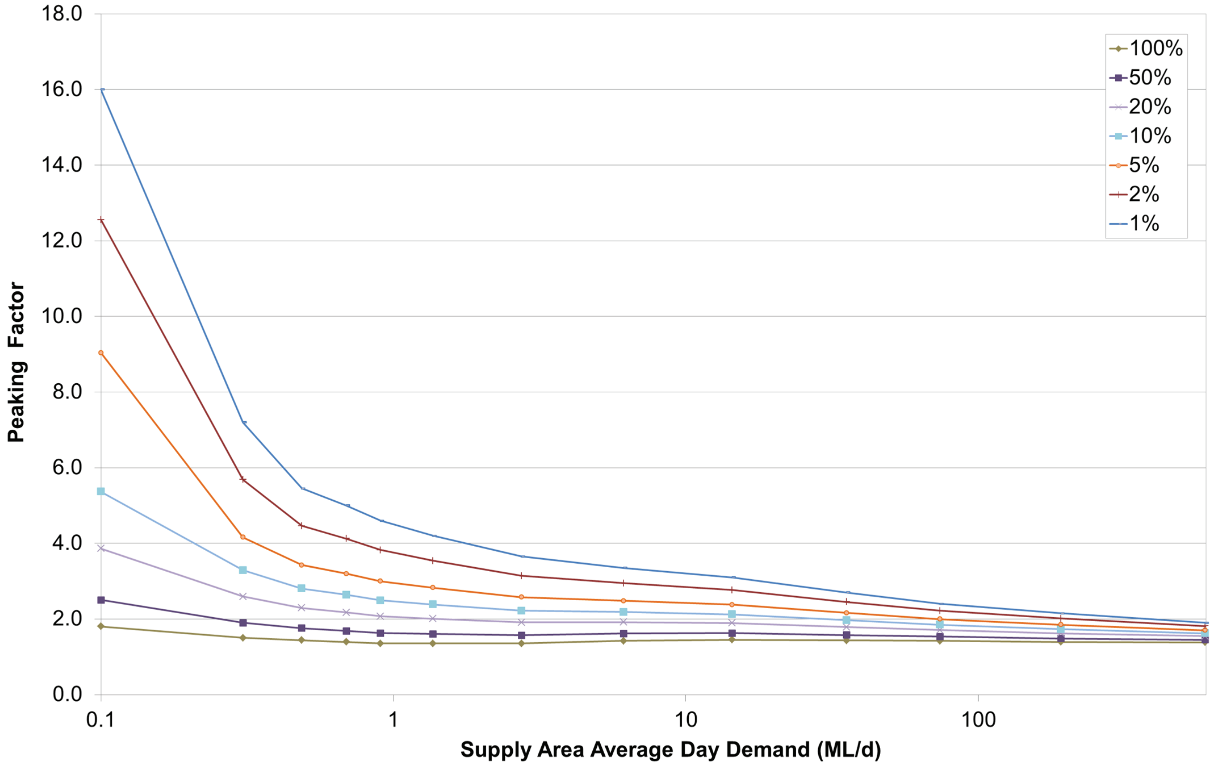

Table 2: 30 Day Peaking Factors

RI	Supply Area Demand *(ML/d)*												
(Year)	0.1	0.3	0.5	0.7	0.9	1.4	2.7	6.1	14.4	35	74	192	597
1	1.20	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.09	1.09
2	1.47	1.26	1.23	1.22	1.22	1.22	1.21	1.20	1.19	1.18	1.17	1.15	1.14
5	1.92	1.51	1.42	1.40	1.40	1.39	1.37	1.35	1.33	1.29	1.27	1.24	1.21
10	2.35	1.72	1.59	1.56	1.55	1.54	1.51	1.48	1.44	1.39	1.35	1.31	1.27
20	2.88	1.97	1.78	1.73	1.72	1.70	1.66	1.61	1.56	1.49	1.44	1.38	1.33
50	3.76	2.36	2.06	1.98	1.97	1.94	1.88	1.81	1.73	1.63	1.56	1.49	1.41
100	4.60	2.70	2.30	2.20	2.18	2.15	2.07	1.98	1.88	1.75	1.66	1.57	1.48

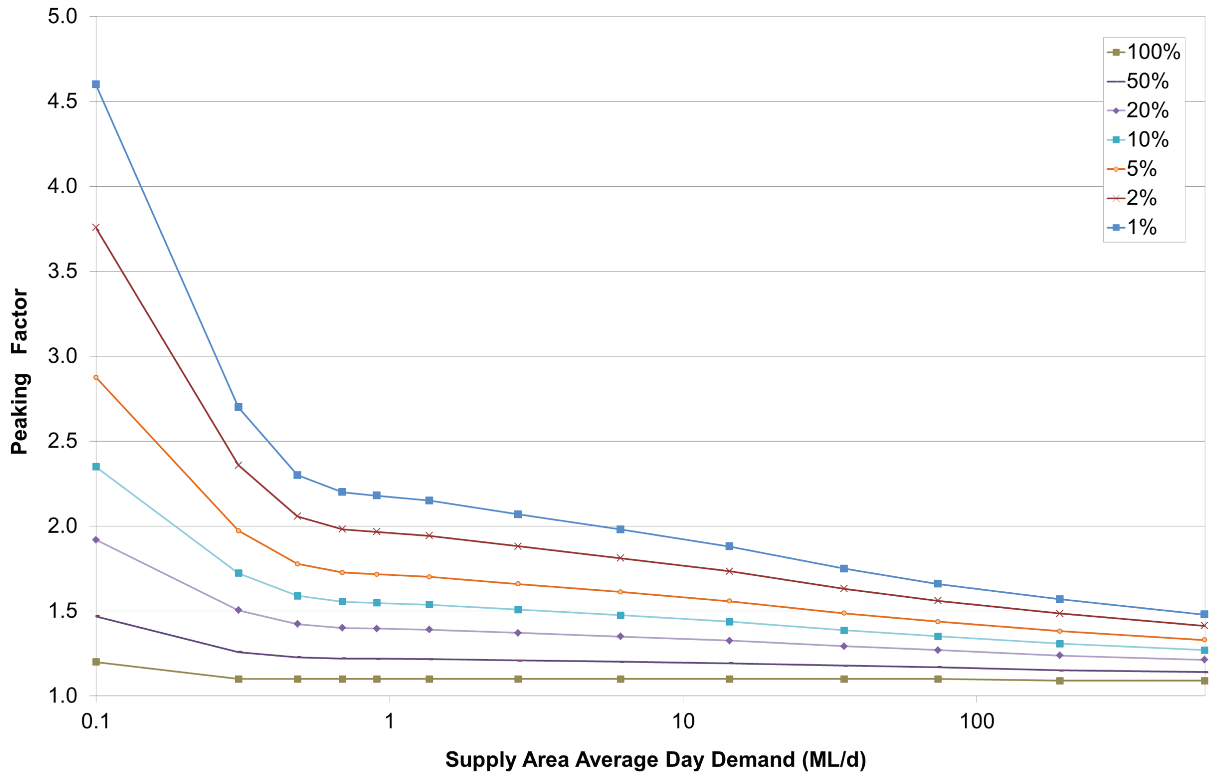

Figure 2: 30 Day Peaking Factor Exceedance Probability Profiles

This paper discusses the application of stochastic peaking factors for undertaking risk assessments.

RISK ANALYSIS

Need for Stochastic Approach

In Australia the national water supply design guidelines (*Water Supply Code of Australia*, WSAA, 2011) recommends that risk assessments are undertaken, *as part of the process of sizing reservoirs and associated pumping stations and determining system configurations. It shall address the available total storage, the relative needs for operating and reserve storage capacity in particular locations and the pumping requirements. The minimum reserve storage provided shall be based on an assessment and costing of the risks associated with the most critical supply interruption.* The WSAA guidelines refer to *AS/NZS ISO 31000:2009 Risk Management – Principles and guidelines*, Standards Australia/New Zealand Standard, 2009 which outline a risk/consequence matrix approach for determining risks and the most appropriate risk mitigation actions.

Risk/consequence matrices can identify the relative need for system reserves, i.e. backup provisions to cope with an identified emergency. Unfortunately, while the risks can be well assessed using these guidelines, the consequences are difficult to evaluate primarily because it is not possible to know whether the emergency event would occur during a minimum day, maximum day or some other value demand event. It is proposed in this document that a stochastic approach is taken for resolving this difficulty in a similar way as storm water drainage structures are sized to suit probable rainfall events.

Independence of Failure and Demand Events

It is common to design water supply infrastructure to meet a maximum level of demand within a certain period of time. If the demand is less than that maximum level, the system operates for a lesser period, or a lower rate, and if the demand is more, the system will still only supply to its maximum capacity. Infrastructure failure events therefore only serve to reduce the capacity of the supply system and generally have no connection with particular demand events. Nevertheless, there are some unique failure events which might be related to the immediate water demand. A very hot day might result in both high water and power demands causing a power outage and in turn a water supply failure. A high rainfall storm event might result in elevated raw water turbidity at a water treatment plant intake causing a loss of treatment capacity while reducing demand within its supply area. But these failure scenarios where some connection with the supply area's demand might be conceived are few, and in no case is it certain that the demand would actually be impacted in the manner suggested. It is therefore proposed for practical purposes that it is accepted that there is no connection between failure and demand events.

This lack of connection, or in other words independence of failure and demand events, normally requires that the maximum demand event must be assumed when considering a combination of the two. However, the provision of back up supplies always capable of meeting maximum demands for all failure scenarios would be very costly. Another approach therefore needs to be taken to this problem. To that end it is noted that a connection between failure and demand events can be made if an approach is taken in which the likelihood of failure is limited to a selected time period.

This is illustrated by the MD peaking factors in Table 1 which show that peaks in demand have probabilities of occurrence and can be sorted by recurrence interval. In other words, the selection of a peaking factor from Table 1 for sizing an item of infrastructure requires that a decision is made about the acceptable likelihood of failure for that infrastructure item.

For example, Table 1 shows that a pipeline supplying an area with an average day demand of 1.4 ML/d would be subject to MD peaking factors of between 1.35 (1 year RI) and 4.2 (100 year RI). The designer might select a 10 year level of service and use the 10 year RI peaking factor of 2.38. In doing so he is setting the infrastructure capacity to be adequate to cope with demands that occur on the average more often than once in 10 years, but would be inadequate for demand events which occur less frequently than once in 10 years.

Risk based connections can also be made between failure and demand events where the failure event is the result of an infrastructure failure. Consider the following sketch (Figure 3) which shows a town supply with a back-up supply.

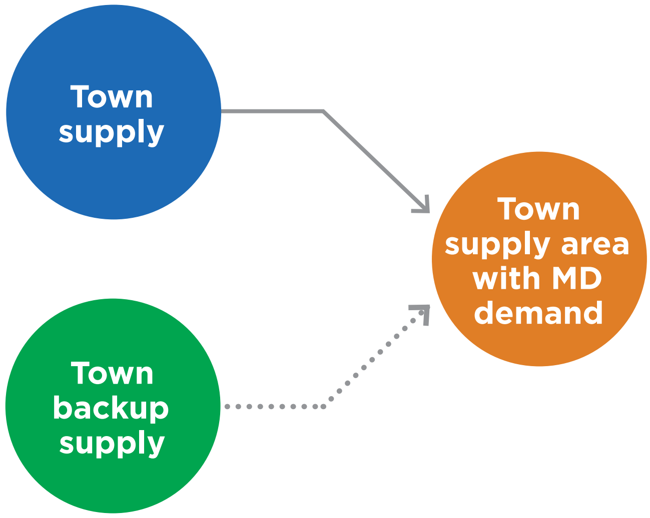

Figure 3: Town Supply and Backup Supply Schematic

The town supply is sized to a level of service as discussed above. The backup supply needs to be sized to the same level of service but its required capacity would be expected to be less than the town supply pipe. This is because the town supply pipe has been sized to carry the maximum demand expected to occur for the adopted level of service. While possible, it is unlikely that a failure event would coincide with a maximum demand event. What then is the probability of a failure occurring within a level of service time period? That can be calculated using the Binomial probability distribution based equation (1) which estimates the probability of occurrence of a failure event with a known failure rate (T) in a period of (N) years.

$$\text{Probability of Occurrence} = 1 - \left(1 - \tfrac{1}{T}\right)^{N} \qquad (1)$$

Using equation (1), the probability of at least one failure associated with an infrastructure failure occurring in a level of service period (*N years*) can be calculated. For example, for a town supply with a risk of failure of, say, once in 8 years and a level of service of 10 years that probability is calculated as follows:

$$\text{Probability of Occurrence} = 1 - \left(1 - \tfrac{1}{8}\right)^{10} = 74\% \text{ within 10 years}$$

Equation (1) implies, for this example, that there would be a need for the town backup supply to be adequate to meet the maximum demand which occurs 74% of the time within a 10 year period. But what is the maximum demand which can occur 74% of the time? It is put forward that the answer lies with the application of Demand Percentiles.

Demand Percentiles

Maximum demand persistence curve values can be calculated from any supply area's twelve-month daily demand record as the maximum 1 day of demand, the maximum 2 days of demand, the maximum 3 days of demand, etc. through to 365 days of demand. Figure 4 shows a maximum, i.e. 100 percentile persistence curve where every point on that curve represents the maximum average peaking factor for a particular demand duration period.

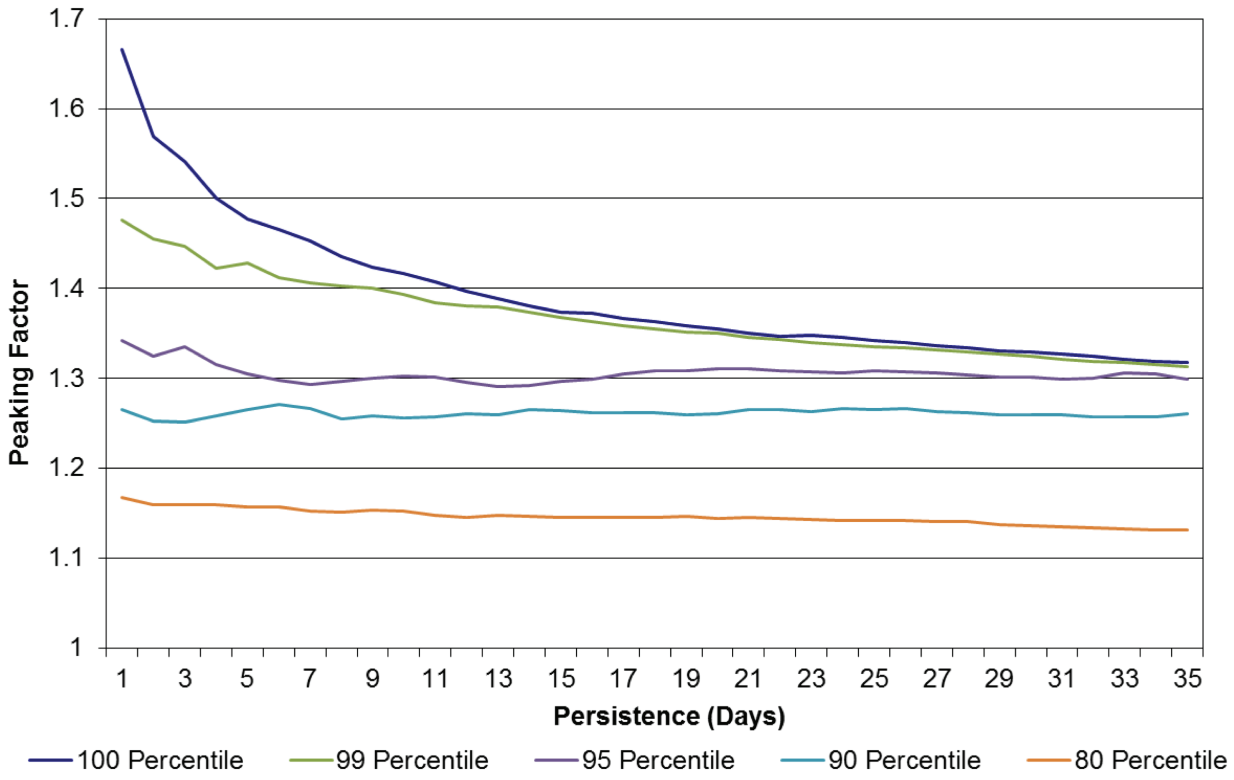

Figure 4: Persistence Curves for Various Demand Percentiles

Figure 4 also includes the 99, 95, 90 and 80 percentile demand persistence curves for the same supply area. (The local rises and falls in the persistence curve values are due to the irregular nature of daily demand data and should be ignored). Whereas the maximum persistence demand curve was derived from a demand record as the maximum of 1 day, 2 days, 3 days, etc. of demand, the 99, 95, 90 and 80 percentile curves are derived in exactly the same manner except that the 99, 95, 90 and 80 percentiles are used instead of the 100 percentile, i.e. maximum values. While Figure 4 only shows the 100, 99, 95, 90 and 80 percentile curves, a curve for any percentile value could be prepared in this manner.

Each curve can be considered as representing that percentile occurrence of the maximum demand event.

For example, the 90 percentile curve represents the maximum demand persistence profile of all those demands which occur up to and including 90 percent of the time. In the paper, *Water Supply Peaking Factor Stochastics*, it is shown that a reasonable representation of any persistence curve can be approximated using the Goodrich Formula (McGhee 1991, p. 14):

$$\textit{Peaking Factor} = A \times \textit{Persistence period}^{\,b} \qquad (2)$$

where *A* equals the MD peaking factor and b is a coefficient which indicates the degree of persistence of demand, and *b* is calculated as a function of the MD and 30 Day peaking factors:

$$b = \text{Log}_{10}\,(\text{30 Day Peaking Factor}/\text{MD Peaking Factor})/\text{Log}_{10}\,(30) \qquad (3)$$

It is noted that equations (2) and (3) are valid for persistence curves of all percentiles.

Reference is again made to the example outlined above for a town supply failure rate of once in 8 years and a level of service of 10 years. Let's assume that Figure 4 represents the demand percentiles for that town supply area and the 100 percentile line represents the maximum day demands for a 10 year recurrence interval, i.e. level of service.

The 74 percentile curve, if drawn, would then represent the maximum of those peaking factors which could occur up to and including 74% of the time. These are the peaking factors to be used for sizing the capacity of the backup supply and their adoption would ensure that, on the average, the peak demand would not exceed the capacity of the town supply more often than once in ten years while subject to a 74% probability of supply failure. Using demand percentiles both the town supply and its backup can be sized to be adequate for demands which, on the average, do not occur more often than once in the same level of service period.

For the purposes of sizing backup infrastructure to meet a level of service, equation (1) can then be rewritten by replacing Probability of Occurrence with Demand Percentile, the failure event recurrence interval (*T*) with Failure Rate, and the supply system failure period (*N*) with Level of Service:

$$\text{Demand Percentile} = 1 - \left(1 - \frac{1}{\text{Failure Rate}}\right)^{\text{Level of Service}} \quad (4)$$

Demand Percentile Peaking Factors

Persistence curves have been prepared from south east Queensland flow meter data for the 99, 98, 95, 90, 80, 70 and 60 percentiles in exactly the same manner as discussed in the paper *Water Supply Peaking Factor Stochastics* for the 100 percentile demands, and as shown on Figures 1 and 2. Probabilistic MD and 30 Day values were subsequently developed for each of those percentiles, again in the same manner previously discussed for the 100 percentile analyses but storage adjustments were only applied to the 95 and greater percentiles because adjustment impacts were found to be insignificant on lesser percentiles.

Full tabulation of all the percentile peaking factors so developed has not been included in this document but is available online in the *Water e-Journal*. However, the 90 percentile MD and 30 Day peaking factor values are set out in Table 3 as an example, and to allow calculation of the worked example below.

Table 3: 90 Percentile Maximum Day and 30 Day Peaking Factors

RI	Supply Area Demand (*ML/d*)												
(*Year*)	0.1	0.3	0.5	0.7	0.9	1.4	2.7	6.1	14.4	35	74	192	597
Maximum Day													
1	1.16	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13
2	1.34	1.26	1.24	1.23	1.23	1.23	1.22	1.22	1.21	1.21	1.20	1.20	1.19
5	1.62	1.45	1.40	1.39	1.38	1.37	1.36	1.34	1.33	1.32	1.31	1.29	1.27
10	1.87	1.61	1.53	1.51	1.50	1.49	1.47	1.45	1.43	1.41	1.39	1.37	1.34
20	2.15	1.79	1.68	1.65	1.64	1.62	1.59	1.56	1.54	1.51	1.48	1.45	1.41
50	2.60	2.07	1.90	1.86	1.84	1.81	1.76	1.73	1.69	1.65	1.61	1.57	1.51
100	3.00	2.30	2.08	2.03	2.00	1.97	1.91	1.86	1.82	1.76	1.71	1.66	1.59
30 Day													
1	1.07	1.07	1.07	1.07	1.07	1.07	1.06	1.06	1.06	1.05	1.05	1.05	1.05
2	1.24	1.17	1.16	1.15	1.14	1.14	1.13	1.12	1.11	1.10	1.10	1.10	1.10
5	1.50	1.33	1.29	1.27	1.26	1.23	1.21	1.20	1.18	1.18	1.17	1.16	1.16
10	1.73	1.46	1.41	1.37	1.35	1.31	1.28	1.26	1.25	1.24	1.23	1.22	1.21
20	2.00	1.61	1.53	1.48	1.45	1.40	1.36	1.33	1.31	1.30	1.28	1.27	1.26
50	2.42	1.82	1.70	1.63	1.59	1.52	1.46	1.42	1.40	1.38	1.37	1.35	1.33
100	2.80	2.00	1.85	1.76	1.71	1.62	1.55	1.50	1.47	1.45	1.43	1.41	1.39

Reliability Analysis Worked Example

The sketch below (Figure 5) shows a hypothetical piped supply from a water treatment plant to a storage tank which supplies a town with an AD demand of 6.1 ML/d (about 30,000 persons). The piped supply crosses a floodplain and a once in 50 year flood event would cause the pipeline to fail in a washout. Its repair would take an estimated three days. How big does its storage tank need to be to ensure that the town does not run out of water? The town council wants at least a once in 100 year level of protection from a loss of its water supply.

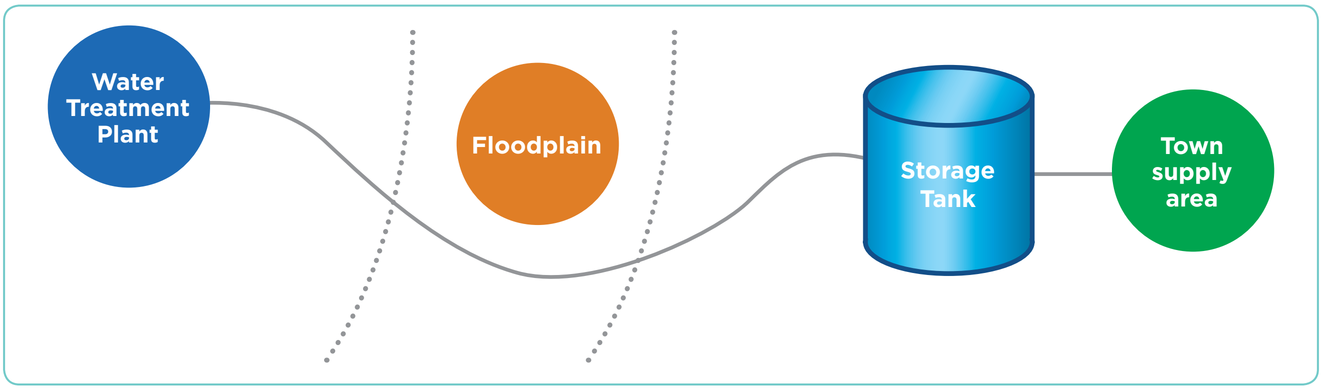

Figure 5: Reliability Analysis Example Scenario

Solution: The Demand Percentile which needs to be allowed for is calculated using equation (4) where the Level of Service is 100 years, and the Failure Rate is 50 years. The Demand Percentile then = $1 - (1 - 1/50)^{100}$ = 0.87, which rounds up to the 90 demand percentile. Table 3 shows the associated MD and 30 Day peaking factors as respectively 1.86 and 1.50.

The required reservoir storage is calculated using the three-day persistence demand peaking factor. That peaking factor is calculated using equations (2) and (3) where *A* equals the MD peaking factor, i.e. 1.86, and $b = Log_{10}(1.50/1.86)/Log_{10}(30) = -0.0635$. The peaking factor for three days of demand then = $1.86 \times 3^{-0.0635} = 1.74$.

The minimum required storage volume to cater for the possible pipeline failure is then the product of the three-day persistence demand peaking factor, three days of pipe failure and the town's Average Day demand, i.e.= 1.74 x 3 x 6.1 = 32 ML.

Backup Provisions

The worked example above calculates the volume of storage needed as a backup for a known failure risk. But backup provisions can take forms other than storage volume, and indeed can include any combination of water sources, water transfer infrastructure and supply area storages which would ensure the same level of service is retained if a normally available infrastructure item was to fail.

A common scenario is a supply which consists of two parallel pipes. Failure of either pipe can be accepted so long as the capacity of the remaining pipe is adequate to meet the demand calculated by equation (4) for the required level of service and the known rate of failure of the failed pipe. Similarly, failure of a water treatment plant serving a water supply area with two treated water sources is an acceptable scenario so long as the capacity of the remaining treatment plant in conjunction with any supply storage is adequate to meet the demand calculated by equation (4) for the required level of service and the known rate of failure of the failed treatment plant.

CONCLUSIONS

Stochastic peaking factors allow risk assessments to be undertaken and the calculation of water supply backup provisions for failure events. While normal and backup water supplies should be designed to the same level of service, normal supplies need to be designed to meet the maximum, i.e. 100 percentile demand, but backup supplies need only be sized to meet the percentile demand defined by the probability of occurrence of the failure event, the level of service and the demand percentile equation.

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THE AUTHOR

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Lee has investigated stochastic methods for the reliability analysis of water supply distribution systems using both optimisation and hydraulic modelling techniques. Those methods have also included the development of the relationships between tank storage volumes, inflow rates and demand persistence. His has been engaged by several south-east Queensland water supply authorities to assess their failure risks with the aim of minimising storage volumes, and in turn system water age.

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