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Sizing Water Distribution Storages for Persistence and Emergency Demands

Balancing conflicting operational and water quality interests

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ABSTRACT

The active volume of a distribution reservoir has only two storage components – diurnal demand storage and persistence storage. No-failure persistence storage provides for peaks in demand not attributable to diurnal variations. Emergency storages, including fire-fighting reserves, are just particular types of failure persistence storage. The persistence storage volume held in a reservoir needs only be the maximum of the calculated no-failure and failure persistence storages.

Persistence demand is well represented as a logarithmic decay function where the decay rate is a function of the supply area's Maximum Day and 30-Day peaking factors. The net persistence storage required for any event is the reservoir persistence demand for the period of the event less than the reservoir inflow during that period. Solving this relationship as a differential equation allows calculation of the critical event period, and the maximum required persistence storage.

Key Words: Water supply; Peaking factor; Stochastic; Demand percentile; Risk; Storage.

INTRODUCTION

There are commonly two conflicting interests when sizing distribution reservoir storages, i.e. operational and water quality. Operational interests seek to maximise storage sizes because a basic role of storage is to provide for supply system failures as an emergency backup supply. Clearly, the greater the storage volume, the less chance the system would run out of water during a system failure. On the other hand, water quality interests seek to minimise storage volumes because of the connection between storage volume and water age and, in turn, disinfection byproduct formation and loss of residual disinfectant.

As a rule of thumb, the volume held in a water distribution system's storages accounts for 70-80% of the total system volume. Hence there is potential to reduce a system's water volume, and water age, through the management of its storages. While the desirable situation would be to have a water supply which was so chemically balanced and low in dissolved organics that water age impacts were insignificant, this is not the case for most systems and an agreement needs to be reached between system reliability and water age.

This paper discusses how an agreement position can be reached which results in a minimum storage volume while providing for all the identified failure risks. It is noted that this paper has been prepared to supplement the suite of companion papers prepared by the same author, *Water Supply Peaking Factor Stochastics* (Donaldson 2018-1), *Water Supply Risk Assessments Using Stochastic Peaking Factors* (Donaldson 2018-2) and *Water Supply Peaking Factor Stochastics and Multiple Levels of Service*, (Donaldson 2018-3).

STORAGE TANK COMPONENTS

Figure 1 shows schematically the storage components of a water supply storage tank.

The unused storage is the air gap above the storage top water level which provides freeboard against overflows.

The dead water storage provides for water impacted by bottom sediments. It is common to assume that 10% of the operational storage is dead water but a better approach would be to adopt a minimum depth, for example 300 mm before the carry-over of sediments is expected to occur.

Figure 1: Reservoir Storage Components

The reservoir's two active storage components are discussed as follows.

Diurnal Demand Storage

Under normal demand conditions storage volumes in all reservoirs rise and fall to a regular pattern between their fill and draw-down phases in response to diurnal changes in demand. The extent of draw down is a function of the setting which commences the fill phase. Some reservoirs, commonly those of small capacity, are controlled by local level probes to draw and fill on a regular basis up to 20 times per day. Other reservoirs have larger fill and draw levels to achieve water turnover. Reservoirs might be set up to only draw and fill a few times per day to limit pumping cycles, or to minimise flow variations and pumping energy in the supply mains. In other cases, reservoirs are primarily controlled to fill at night and draw down during the day to take advantage of off-peak electricity charges.

The minimum volume which allows for the diurnal demand is broadly estimated as 4 hours of the Average Day peak hour demand.

Persistence Storage

Persistence storage provides for peaks in demand not attributable to diurnal variations. The volume of persistence storage needed is a function of the capacity of the supplying mains to the reservoir. There are peaks in demands associated with both no-failure and failure events. Emergency storage and fire-fighting storage are failure types of persistence storage. The Figure 1 persistence storage volume needed in a reservoir is the greatest persistence volume after assessing all no-failure and failure scenarios.

PERSISTENCE STORAGE CALCULATION

The focus of this paper is the persistence storage volume component, and identification of the factors which influence that volume. Discussion about the estimation of no-failure volumes using demand persistence and demand stochastics follows.

Demand Persistence Curves

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. The 1 day demand persistence is called the Peak Day or Maximum Day (MD) demand and the 365 day demand persistence period is called the Average Day (AD) demand. The 30 day persistence is sometimes called the Mean Day Maximum Month but is named the 30 Day demand in this paper.

Persistence curves have long been recognised as taking the form of a logarithmic decay function. Equation (1) shows the Goodrich Formula (McGhee (1991), p. 14) which is sometimes quoted in text books for estimating the maximum day demand *P* for a time *t* as a percentage of the annual average demand.

$$P = 180.t^{-0.10} \quad (1)$$

While the Goodrich Formula is based on a fixed one-day maximum day peaking factor of 1.8 and a maximum persistence period of 365 days, that equation can be generalised as:

$$Peaking\ Factor = MD \times Persistence\ period^{b} \quad (2)$$

where *MD* equals the actual one-day peaking factor and *b* is a logarithmic decay coefficient which indicates the degree of demand persistence, and is calculated in this paper as a function of the MD and 30 Day peaking factors:

b = Log10 (30 Day Peaking Factor / MD Peaking Factor) / Log10 (30) (3)

Equation (2) in conjunction with equation (3) is generally only valid for persistence periods of less than about 35 days because it is limited by the 30 Day demand peaking factor. Figure 2 shows a typical persistence curve prepared from a twelve-month flow meter record overlaid with the representative curve prepared using equations (2) and (3). It illustrates the high correlation with actual data records which can be achieved using those equations.

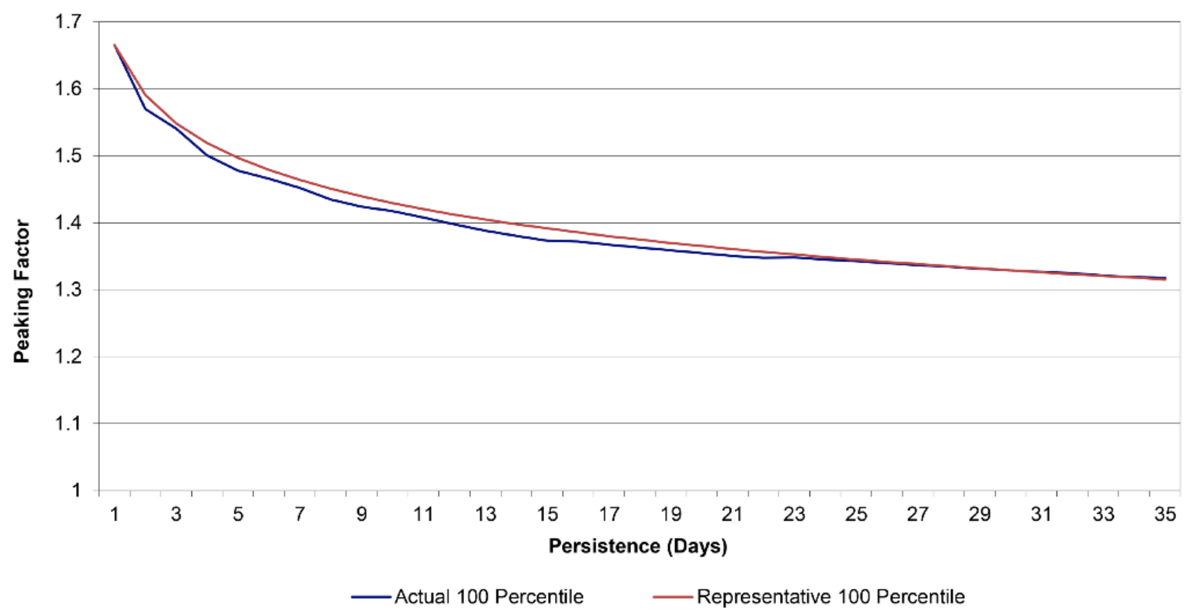

Figure 2: Example of Actual and Representative Persistence Curves

Persistence Storage Calculation

Persistence curves are useful for determining the required persistence storage volume for a supply area.

That storage is generally calculated as the demand less the inflow, i.e.:

$$Persistence\ Storage = Peaking\ Factor \times Average\ Day\ Demand \times Persistence\ Period - Inflow\ Rate \times Persistence\ Period \quad (4)$$

The persistence period for the maximum required persistence storage is the unknown in equation (4) but can be determined by the combination of equations (2), (3) and (4) as a function of the persistence period and solving as a differential equation for the maximum storage volume.

Equations (5) to (8) summarise that determination where *MD* = MD Peaking Factor, *PP* = Persistence Period, *b* = logarithmic decay coefficient, *I* = Inflow/AD (dimensionless as a function of the Average Day demand), and *V* = Persistence Storage/AD (also dimensionless as a function of the Average Day demand):

$$V = MD.PP^{b}.PP - I.PP \quad (5)$$

$$V = MD.PP^{(1+b)} - I.PP \quad (6)$$

$$\frac{dV}{dPP} = MD.(1+b).PP^{b} - I = 0 \quad (7)$$

$$PP = \left\{\frac{I}{MD.(1+b)}\right\}^{1/b} \quad (8)$$

Expansion of equation (8) then gives:

$$Critical\ Persistence\ Period\ for\ maximum\ volume = \left[\frac{Inflow/_{AD}}{MD\ Peaking\ Factor\ \times (1+b)}\right]^{(1/b)} \quad (9)$$

where *b* is the logarithmic decay coefficient calculated using equation (3).

The maximum required persistence storage is then calculated from equation (10):

$$Persistence\ Storage = \Big(MD\ Peaking\ Factor \times Critical\ Persistence\ Period^{(1+b)} - Critical\ Persistence\ Period\ \times \frac{Inflow}{AD}\Big) \times AD \quad (10)$$

Maximum Storage-Inflow Curve

Equations (9) and (10) are better appreciated when they are visually presented as a maximum storage-inflow curve. A maximum storage-inflow curve allows optimisation of the capacities of a supply area's storage and its inflow main. Anderson and Vickers (1989) described their application for optimising the size of storage supply mains of greater than 20 km length where it is much more economical to reduce the supply pipe diameter, and the flow rate, and increase the storage capacity.

Figure 3 is a plot of the maximum required storages for an example supply area with MD and 30 Day peaking factors of respectively 2.2 and 1.5. The corresponding Critical Persistence Periods are shown as red-coloured data points on that figure.

Both the storages and inflows are dimensionless and plotted as ratios of the AD demand. Figure 3 shows, for instance, if the supply area had an inflow equal to 1.7 times the AD demand the maximum required persistence storage for all persistence periods is 0.74 times the AD demand. As would be expected, no persistence storage would be needed if the inflow is equal to or greater than the MD ratio to the AD (i.e. 2.2 in the Figure 3 example).

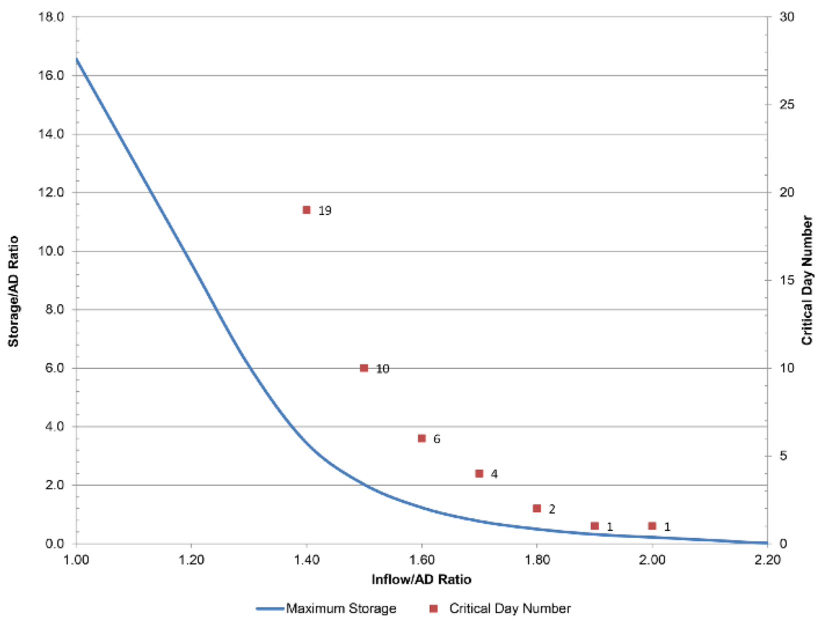

Figure 3: Example: Maximum Storage-Inflow Curve

FAILURE STORAGE CALCULATION

Demand Percentile Equation

The companion papers, *Water Supply Peaking Factor Stochastics* (Donaldson 2018-1) and *Water Supply Risk Assessments Using Stochastic Peaking Factors* (Donaldson 2018-2), show that flow records represent a supply area's demand and from those records, MD and 30 Day peaking factors can be stochastically developed with respect to the supply area's AD demand for any demand percentile. It is also shown that there is a relationship between the demand percentile for a supply area's backup, the failure rate of the normal supply, and the adopted level of service. That relationship is set out in equation (11):

$$Demand\ Percentile = 1 - \left(1 - \frac{1}{Failure\ Rate}\right)^{Level\ of\ Service} \quad (11)$$

Equation (11) allows calculation of the demand percentile which determines the peaking factor associated with a failure event. All demand percentile peaking factors for the south-east Queensland supply area have been tabulated (Donaldson 2018-4). This Peaking Factor Table ("the online PF Table") is available online at http://awa.asn.au/documents/Percentile_Peaking_Factors.pdf [1], and a worked example of the use of equation (11) is included in the companion paper *Water Supply Risk Assessments Using Stochastic Peaking Factors*. It is noted that the demand percentile for a no-failure event is, by definition, the 100th percentile whereas a failure event with a failure rate longer than one year must have a lesser demand percentile.

The term "failure event" is any non-usual event which can impact on a supply system and includes pipe, pump and power supply failures, and demand events such as those associated with fire-fighting events. However, use of the Demand Percentile equation (11) for determining the peaking factor associated with a failure event requires some additional considerations. These are discussed as follows.

Level of Service

The *Level of Service* (LOS) in equation (11) is the acceptable frequency of failure where failure is defined as the loss of water supply. The companion paper, *Water Supply Peaking Factor Stochastics and Multiple Levels of Service* (Donaldson, 2018) proposed an algorithm, equation (12), for calculating the LOS based on arbitrary weightings for the supply area's residential, non-residential and community populations.

$$Level\ of\ Service = 10 \times e^{Affected\ Supply\ Area\ Score} \quad (12)$$

The *Affected Supply Area* Score is calculated by summing the residential population divided by 600,000 and the equivalent person non-residential population divided by 125,000. While equation (12) and these weightings are clearly arbitrary, their use results in a LOS gradually rising from a minimum of 10 years as the supply area's importance increases. That 10 year minimum is primarily based on advice given in the Hunter Water edition of the Water Supply Code WSA 03 (WSAA, 2009).

Failure Rate

Determination of the failure rate of a water supply system involves assessing the probability of failure of the supply system components and estimating the risks and associated outage times for the component combinations. The assessment of risk combinations is often undertaken using a fault tree analysis, but the simplicity of a typical distribution system permits use of only the AND and OR gates provided for in Boolean logic. Figure 4 shows a schematic of a simplified typical water supply distribution system where the storage provides backup against the possible failure of its treatment plant, pump station and pipelines, or some combination of those failures.

[1] *Alternatively, a hyperlink to the PF Table can be found on page 6 of Donaldson 2018-2. Click on the light blue text appearing immediately before Table 3 of that paper.*

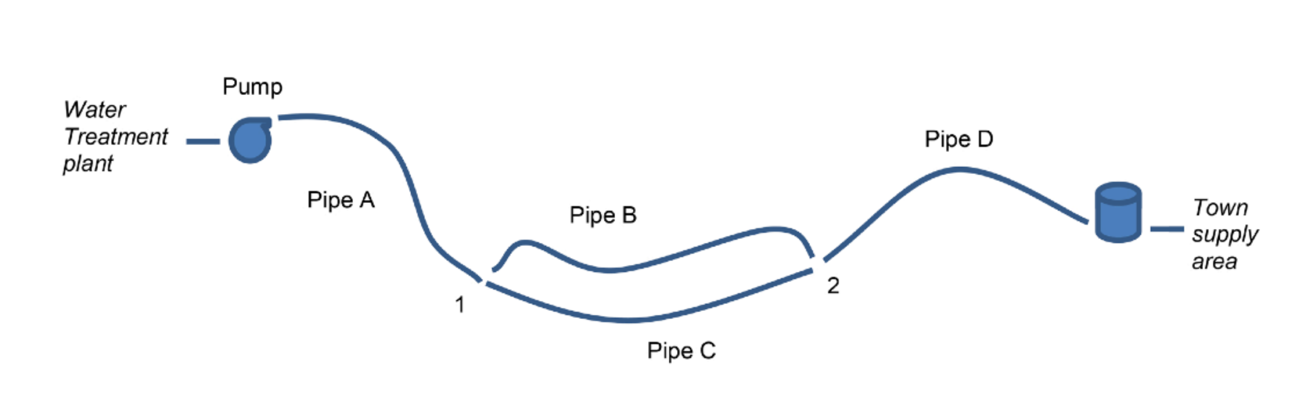

Figure 4: Typical Distribution System Supply to Storage

The *Failure Rate* used in equation (11) is the combination of the failure probabilities of the individual components supplying the storage. Boolean logic states that the combined probability of two independent events is the addition of each event's occurrence probability (an AND gate), and for two dependent events it is the multiplication of each event's occurrence probability (an OR gate). The probability of full loss of supply to the town storage is then calculated by combining the supply system's element failure probabilities as follows:

$$Water\ treatment\ plant + Pump + Pipe\ A + (Pipe\ B\ \times Pipe\ C) + Pipe\ D \qquad (13)$$

This combination of probabilities is only valid if the failure of each element has the same consequence, i.e. full loss of supply to the storage. Pipes B and C need to be combined as an OR gate to obtain that result because failure of either pipe by itself would not result in a complete loss of supply. Nevertheless, it is noted that for supply systems which include parallel elements, e.g. Pipes B and C in Figure 4, there might be scenarios where the extended failure of one of the parallel pipes requires a greater storage provision even though the system still retains some flow capacity to the storage.

Supply Outage

Estimation of the failure rate and LOS allows calculation using equation (11) of the demand percentile, and in turn the peaking factor associated with a failure event. A hydraulic model could then be set up with, for example, a pipe failure and an associated demand peaking factor but this is not enough for the analysis of water supply systems where storages are included because the probable outage time is also needed.

That outage time is calculated by multiplying the unavailability of each supply system element by its probability of failure. Unavailability (hours per annum) of a supply element is calculated by dividing its outage time by its failure rate. The combined unavailability of elements in series is the sum of the individual elements' unavailability. The combined unavailability of parallel elements is calculated as the minimum outage time of the parallel elements multiplied by their combined failure probability. Use of the larger of the two times would be wrong because it ignores that the other pipe would not have failed for some part of that time. The unavailability of the Figure 4 example is therefore the following combination of its element unavailabilities and failure probabilities.

$$Water\ treatment\ plant\ unavailability + Pump\ unavailability + Pipe\ A\ unavailability + Minimum\ (Pipe\ B\ outage, Pipe\ C\ outage) \times (Pipe\ B\ failure\ probability \times Pipe\ C\ failure\ probability) + Pipe\ D\ unavailability \qquad (14)$$

The combined outage time of full loss of supply for that example is then the product of the combined unavailability and combined failure probability.

Combination of Failure Rate and Outage

Infrastructure failure rates and outage times are not unique, and both have probabilistic distributions. A large spectrum of possible failure rate and outage time combinations exists for every pipe and pump in a supply system. It is generally not possible to generate all those combinations because water supply infrastructure failure data is generally sparse and at best is usually quoted as only an average rate. Fortunately, infrastructure outage times are more available and are even sometimes quoted as 5, 50 and 95th percentile values. Those average failure rates and the 5, 50 and 95th percentile outage times can then be combined to provide three failure options:

- 5th percentile Outages – Combination of failure rate multiplied by 0.95 and 5th percentile outage time
- 50th percentile Outages – Combination of failure rate multiplied by 0.5 and 50th percentile outage time
- 95th percentile Outages – Combination of failure rate multiplied by 0.05 and 95th percentile outage time

The outcomes of these three options can be tested using equation (11) to calculate the demand percentiles, and in turn the associated demand peaking factors. For example, it might be found that the peaking factors associated with a 5th percentile outage when combined with the 5th percentile failure time has a greater storage requirement than the peaking factors associated with a 50th percentile outage combined with the 50th percentile failure time.

Fire-fighting Reserve

It is noted that there is no reference to a fire-fighting reserve in Figure 1 because fire events are considered to be just another emergency event. Fire-fighting water main pressures are required by AS2419.1 - Fire Hydrant Installations to be available 95% of the time, and the 95th percentile peaking factor values are listed for the south-east Queensland supply area in the online PF Table (Donaldson 2018-4).

Failure Persistence Storage Calculation

Equation (10) is again applied for the calculation of the required failure persistence storage using the MD peaking factor determined after calculating the Demand Percentile (equation (11)) for the failure event, and the MD and 30 Day Peaking Factors from the online PF Table (Donaldson 2018-4). If the failure event reduces the time of inflow to the storage, equation (10) needs to be amended as shown in equation (15).

$$Failure\ Persistence\ Storage = \Big(MD\ Peaking\ Factor \times Critical\ Persistence\ Period^{(1+b)} - (Critical\ Persistence\ Period - Failure\ Time) \times \frac{Inflow}{AD}\Big) \times AD \qquad (15)$$

where the *Critical Persistence Period* cannot be less than the *Failure Time*.

RESERVOIR STORAGE WORKED EXAMPLE

A hypothetical town water supply in south east Queensland needs a new reservoir. The reservoir will be gravity supplied by an existing pipeline connected to a highly reliable water supply grid. The pipeline, however, has a known history of failures and has only a fair reliability. The reservoir needs to be sized to include adequate failure storage to allow for the repair of the pipeline when it fails. Figure 5 conceptually shows the water supply system.

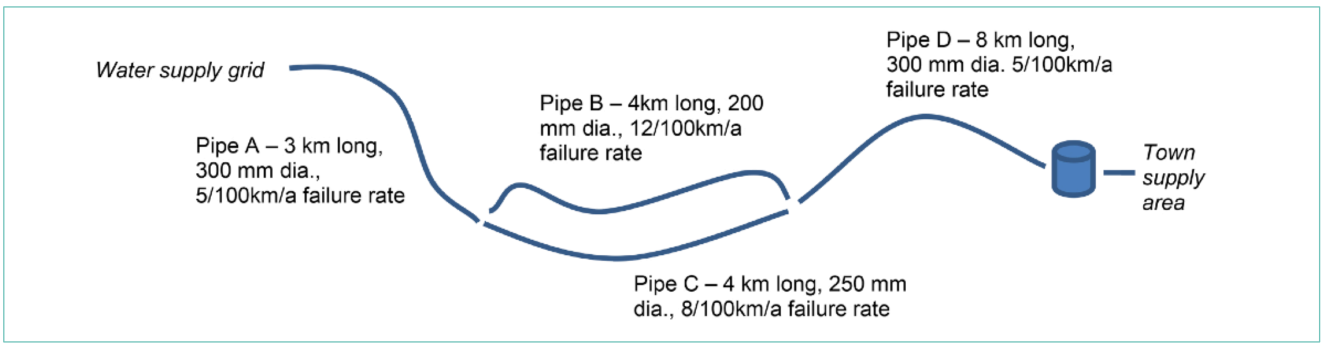

Figure 5: Example: Water Supply System

The design water supply demand is 24,000 equivalent persons made up of 18,000 residential and 8,000 non-residential persons. The average day design demand is 4.7 ML. The pipeline has a transfer capacity of 7.6 ML/d.

There are three steps to be worked through to determine the required reservoir volume:

No-failure Persistence Storage

Using equation (12) the Level of Service for this water supply is calculated as 10.9 years. From the online PF Table (Donaldson 2018-4) the MD and 30 Day peaking factors for a supply area with an average day demand of 4.7 ML and a Level of Service of 10.9 years are respectively 2.23 and 1.51. Using equations (3), (9) and (10) the no-failure persistence storage equals 5.6 ML.

Failure Persistence Storage

Table 1 sets out the four pipes which make up the pipeline supplying the proposed new reservoir with their historical failure rates as shown on Figure 5.

Also included are the 5, 50 and 95 percentile repair times if the pipes were to fail. These have been developed from the town water authority's operational experience. These failure rates and outage times have been broken into three groups, *5th percentile Outages*, *50th percentile Outages* and *95th percentile Outages* as described above, and *Combined Pipe Failures* using equations (13) and (14).

Table 1: Example Water Supply System Combined Failures

	Pipe Failure Rates and Outage Times				5%ile Outages			50%ile Outages			95%ile Outages		
Pipeline Element	Failure Probability	5% Outage Time *(Hours)*	50% Outage Time *(Hours)*	95% Outage Time *(Hours)*	Failure Rate	Unavailability *(Hours per annum)*	Outage *(Hours)*	Failure Rate	Unavailability *(Hours per annum)*	Outage *(Hours)*	Failure Rate	Unavailability *(Hours per annum)*	Outage *(Hours)*
A	0.150	4.0	8.0	14.0	0.143	0.57	4.0	0.075	0.60	8.0	0.008	0.11	14.0
B	0.480	3.0	6.0	11.0	0.456	1.37	3.0	0.240	1.44	6.0	0.024	0.26	11.0
C	0.320	3.0	7.0	13.0	0.304	0.91	3.0	0.160	1.12	7.0	0.016	0.21	13.0
D	0.400	4.0	8.0	14.0	0.380	1.52	4.0	0.200	1.60	8.0	0.020	0.28	14.0
Combined Pipe Failures					0.661	2.51	3.8	0.313	2.43	7.8	0.028	0.39	14.0

Table 1 shows the three combined pipe failure scenarios as follows:

- 5th percentile Outages – A combined failure rate of 0.661, (~ once in 2 years) with an associated outage time of 3.8 hours.
- 50th percentile Outages – A combined failure rate of 0.313, (~ once in 3 years) with an associated outage time of 7.8 hours.
- 95th percentile Outages – A combined failure rate of 0.028, (~ once in 36 years) with an associated outage time of 14 hours.

Using equation (11) with a Level of Service of 10.9 years, the demand percentiles for these three failure scenarios are calculated as respectively 99.99%, 98.4% and 26.6%. As for the no-failure case, the MD and 30 Day peaking factors are looked up from the online PF Table (Donaldson 2018-4). The required persistence storage for the three failure scenarios are then calculated using equations (3), (9) and (15) as follows:

- 5th percentile Outages – 6.8 ML
- 50th percentile Outages – 3.0 ML
- 95th percentile Outages – 2.7 ML

Reservoir Volume

The required reservoir volume is the sum of the dead water allowance, the diurnal demand storage, the freeboard allowance and the maximum of the no-failure and failure persistence storage volumes (i.e. the maximum of 5.6, 6.8, 3.0 and 2.7 = 6.8 ML).

This worked example has only considered the persistence storage requirements for the no-failure and pipe failure scenarios. A more complete assessment would also have included the fire-fighting demand scenario, but in practice it would be unusual for that scenario to require the greatest persistence storage.

CONCLUSIONS

The active volume of a distribution reservoir has only two storage components – diurnal demand storage and persistence storage. No-failure persistence storage provides for peaks in demand not attributable to diurnal variations.

Emergency storages, including fire-fighting reserves, are just particular types of failure persistence storage and the persistence storage volume held in a reservoir needs only be the maximum of the calculated no-failure and failure persistence storages.

Persistence demand can be represented as a logarithmic decay function where the decay rate is a function of the supply area's MD and 30 Day peaking factors. The net persistence storage required for any event is the reservoir persistence demand for the period of the event less than the reservoir inflow during that period. Solving this relationship as a differential equation will determine the critical event period, and the maximum required persistence storage.

Persistence demand during a no-failure and a failure event is calculated in the same manner except that the MD and 30 Day peaking factors for failure events are defined by the Demand Percentile equation which is a function of the event's failure rate and the LOS adopted for the supply area. The peaking factors for no-failure events are, by definition, those associated with the 100th percentile demand.

The level of service adopted for a supply area used in the Demand Percentile equation is the same for both no-failure and failure events. Infrastructure failure rates used with failure events need to include all elements in the supply delivery chain to the reservoir and should be combined using Boolean algebra. Outage times should be similarly combined. Calculating the persistence storage for failure events with combinations of failure rates and outage times can identify the maximum required failure persistence storage.

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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. He 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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