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Reliability analysis of municipal storage reservoirs using stochastic analysis

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Water distribution systems operate under constantly varying conditions that display both deterministic and probabilistic behaviour. Design guidelines, on the other hand, typically specify reservoir storage capacity in terms of deterministic parameters only. A method is presented for analysing the reliability of municipal storage reservoirs based on stochastic models of water demand, pipe failures and fire events. The method was applied to the Yeoville water supply system in Johannesburg and showed that its reservoir complex has a good level of reliability even though it is significantly smaller than required by the South African design guidelines. The analysis considered a number of layout changes to the supply network which could have significant impacts on the reservoir reliability. In conclusion, it is shown that the sporadic demands of fire flow do not significantly affect the reliability of the Yeoville reservoir complex.

INTRODUCTION

Water distribution systems operate under continuously varying conditions caused by a range of factors such as rainfall, temperature fluctuations, fires, pipe and power failures, maintenance events and human actions. While most of these factors exhibit complex behaviours reflecting both deterministic and probabilistic elements, water distribution systems are normally designed using only deterministic design parameters such as average demands, peak factors and fire flows. Municipal storage reservoirs, in particular, are typically sized according to deterministic demand balancing, emergency storage and fire requirements (Haarhoff *et al* 2000).

A larger capacity will allow a reservoir to satisfy larger demands, thereby improving its reliability. On the other hand, increased reservoir capacity translates into increased costs and longer retention times, which may affect water quality negatively. The design engineer has to strike an appropriate balance between these conflicting considerations.

Unlike water distribution systems, where no definition of reliability has been universally accepted (Walski *et al* 2003), the reliability of a storage reservoir can be clearly defined in terms of its ability to supply water to its users: a reservoir fails when it runs empty and is operational otherwise. Its reliability (or lack thereof) can thus be described in terms of its probability of failure. Various failure parameters can be used, including the number of failures, failure duration or reservoir fail time (product of the average number of failures and average failure duration), any of which may be critical depending on local requirements. Since the reservoir fail time incorporates both the number of failures and failure duration, it is used as measure of reservoir reliability throughout this paper.

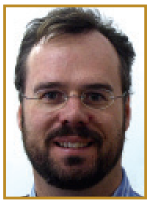
This paper proposes a stochastic method for the analysis of storage reservoir reliability in water distribution systems that can take the specific conditions at a reservoir into account. Methods to model network parameters and storage reservoir reliability using stochastic techniques are discussed and the proposed method is applied in a case study to demonstrate its potential benefits. Application to the Yeoville bulk supply system indicated that considerably smaller reservoir capacities can be used than those specified in design guidelines, which are inherently conservative.

METHODOLOGY

Introduction

A stochastic model generates outputs which are predictable only in a statistical sense. Repeated use of a given set of model inputs produces outputs vary but follow certain statistical patterns (Haan 1977; Lewis 1996). Stochastic modelling is frequently used in the analysis of complex systems where risk and uncertainty play important roles. It is an established technique in various engineering disciplines, including water source analysis, electrical power distribution and communications networks (Yang *et al* 1996).

Stochastic analysis has been applied to water distribution systems in a number of previous studies (Damelin *et al* 1972; Wagner *et al* 1988; Bao & Mays 1990; Yang *et al* 1996), although these studies focused mainly on link failures. Nel and Haarhoff (1996) and Haarhoff and Van Zyl (2002) performed stochastic analyses to estimate



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reservoir reliability incorporating stochastic models for water demand, pipe failures and fire events, but these studies were limited to simple systems where the reservoirs were connected to single pipes, obviating the need for hydraulic analysis. This method was extended in this study by incorporating full hydraulic modelling capabilities and thus allowing complex networks to be analysed.

The function of a reservoir is to balance differences between supply and demand: the storage volume in the reservoir will increase if supply exceeds demand, and decrease if demand exceeds supply. The buffering ability of a reservoir is limited by its maximum capacity and current storage volume.

The demands from a reservoir are conveniently classified as user demands, fire fighting demands and leakage. Demands cannot exceed the hydraulic capacity of the network linking the reservoir with its users. Supply to a reservoir is a function of the capacity of the source and the pipe system supplying the reservoir. Pipe failures can affect both the supply and demand in a water distribution system: failures in the supply network can reduce the reservoir inflow, while pipe failures in the demand network can reduce the outflow from the reservoir (for example by disconnecting certain users), or increase the demand in the case of major pipe bursts. Water losses, source and pump failures were not considered as part of this study.

Methodology

The stochastic analysis method is based on Monte Carlo simulation (Fishman 1995), which entails the repeated calculation of the system performance, each time with a different combination of input parameters. The method was implemented using the public domain software Epanet (Rossman 2000) and OOTEN (Van Zyl *et al* 2003), an object-oriented programmers toolkit for Epanet.

Stochastic unit models were used to simulate the stochastic behaviour of consumer demands, pipe failures and fire demands. Consumer and fire demands were calculated and implemented using standard Epanet demand patterns. Pipe failures were implemented by closing and opening pipes using Epanet controls. Once the parameters for the daily simulation were set, the system hydraulics for the day were calculated using hourly time steps (and intermediate time steps when required) and the system performance was evaluated. Events such as pipe failures, fires, and various other parameters such as the pressure at nodes or flows in pipes could be logged if required. The reservoir under investigation is modelled as a source (that is, it is not allowed to fail) and the performance of different reservoir capacities are calculated based on the reservoir in- or outflows in each time step. After the required number days were simulated, the performance of the system was reported statistically.

There is no general rule for determining the number of iterations required to obtain good results in a stochastic analysis and it is necessary to perform a sensitivity analysis in which the simulation is run for an increasing number of iterations until the results for the required parameters converge.

Events such as pipe failures and fires can create network conditions that are problematic to model and certain alterations to the Epanet hydraulic engine were thus required. Events that had to be catered for included reservoirs running dry, sections of the network that can be isolated from a water source, and low or negative nodal pressures.

Sections of a network with demands that are isolated due to reservoirs running dry or pipe failures prevent the Epanet hydraulic solver from converging on a solution. As soon as a problem with convergence was found in a simulation run, the network connectivity was checked to identify isolated sections. The isolated sections were handled by first setting all their demands to zero (which solves the convergence problems), then running the hydraulic solver and finally setting all pressures in the isolated sections to zero.

In certain cases, a pipe failure or fire demand could cause pressures at nodes to become low or even negative in the demand-driven model used by Epanet. Strictly speaking, demand flow rates are not fixed since node outflows occur via orifices (for example open taps or valves) and are thus dependent on the pressure in the system. However, this relationship is generally ignored in hydraulic analysis (Reddy & Elango 1989) and known demand values are imposed on the system as functions of time only. While this assumption gives good results for normal operating pressures, is does not provide an accurate model of the system behaviour under failure or abnormally low pressure conditions (Germanopoulos 1985). To handle conditions of abnormally low pressure, a critical pressure was defined as the minimum pressure at which demand will not be affected by pressure. Above the critical pressure the nodal demand was fixed. At a pressure below zero the demand was set to zero, and for a pressure between zero and the critical pressure the demand was modelled as a function of pressure using a modified version of the Epanet emitter facility. At the end of each snapshot simulation, the software checked for demand nodes with pressures below the critical pressure. If such nodes were found, the fixed demands at these nodes were changed to pressure-dependent demands (orifices) and the simulation repeated to obtain the correct results.

Stochastic input models

Three stochastic input models were used in this study: for consumer demand, pipe failure events and fire-fighting demand. Input models should ideally be based on measured data of the system, but where this is not possible, assumed model parameters can be based on similar areas or engineering judgement. The types and details of the input models vary depending on the purpose of the simulation and the properties of the available data. It is thus not possible to develop input models that will be suitable for all types of analyses.

Various water demand models have been proposed by different researchers, including extrapolation (Billings & Jones 1996), exponential smoothing (Brdys & Ulanicki 1994), multiple regression (Billings & Agthe 1998), expert systems (Hartley & Powell 1991), neural networks (Brdys & Ulanicki 1994), end-use (Van Zyl *et al* 2003b) and stochastic (Shen 1976) models. For this study, a model with both stochastic and deterministic elements was used as described by the equation:

$$D_{hour} = F_{hour}[(D_{ave} \times F_{seas} \times F_{dow} \times F_{prop})\\ (1 - F_{acor}) + (D_{pday} \times F_{acor})]$$

Where D_{hour} the hourly demand, D_{ave} the annual average daily demand, D_{pday} the previous day's average demand, F_{hour} the hourly peak factor, F_{seas} the seasonal peak factor, F_{dow} the day-of-the-week peak factor, F_{prob} a probabilistic hourly peak factor, and F_{acor} the one-day auto correlation coefficient. Autocorrelation occurs when residuals from adjacent measurements in a time series are not independent of one another. This study was limited to a one-day autocorrelation coefficient only. The probabilistic factor represents the random behaviour of water demand and was applied to adjust the daily demand using random distributions fitted to, or assumed for the demand data.

Two key parameters are required for the description of pipe failure, namely the probability of failure and the duration of the resulting supply interruption. Pipe failures occur relatively infrequently (Clark *et al* 1982) and records, if they are kept, are not often published. Many factors play a role in pipe failure behaviour, including material, diameter, age, number of previous failures, internal pressure, external loading, construction quality, climate, soil properties and maintenance practices. Data on failure duration are even harder to obtain, but a good estimate can be made by investigating maintenance reports and interviewing repair teams.

While some pipe failure studies could be accessed (GLS 1995; Kettler & Goulter 1985; Van der Mey 1995; Nel 1993), presenting a general balanced picture is difficult as a result of differences in the study methods

Table 1 Pipe failure rates reported in a number of studies

Material	Diameter (mm)	Failure rate (/100 km/a)
AC	50–300	5–163
Cast iron	100–500	5–106
Ductile iron	100–500	16–30
PVC	90–500	4–35
Steel	100–1 000	4–58

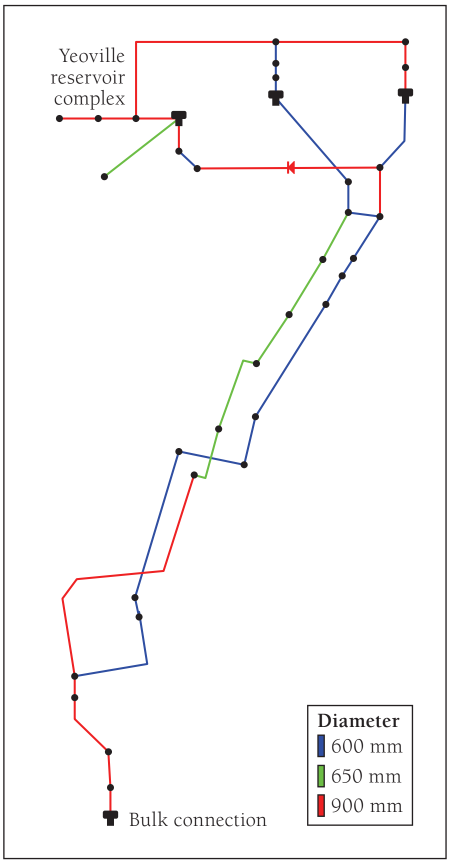

Figure 1 Schematic layout of the Yeoville bulk supply system

and presentation of the results. However, certain trends are evident, for instance a noted reduction in failure rate with increasing pipe diameter. A range of failure rates for different pipe materials are summarised in table 1.

To model fire water demands stochastically, the fire frequency, duration and flow rate have to be described. These parameters are best estimated by analysing fire authority records. A simpler, more direct approach is to estimate some model parameters from design guidelines. Design guidelines usually specify both the maximum fire flow rate and the fire duration as a function of the land use category, population density, or other factors.

CASE STUDY

Some of the benefits of the procedure outlined above are illustrated through a case study of the Yeoville bulk supply system, which forms part of the Johannesburg water supply system.

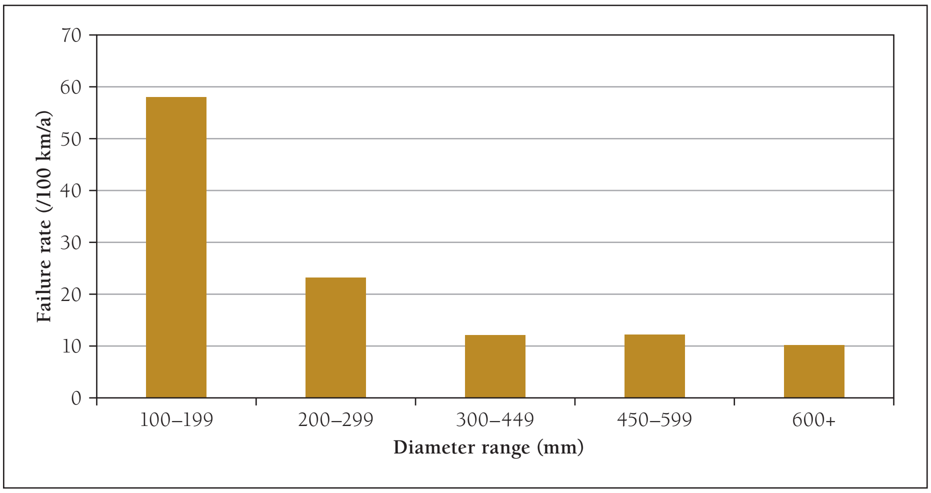

Figure 2 Average failure rate of Johannesburg steel pipe as a function of pipe diameter (from Van der Mey 1995)

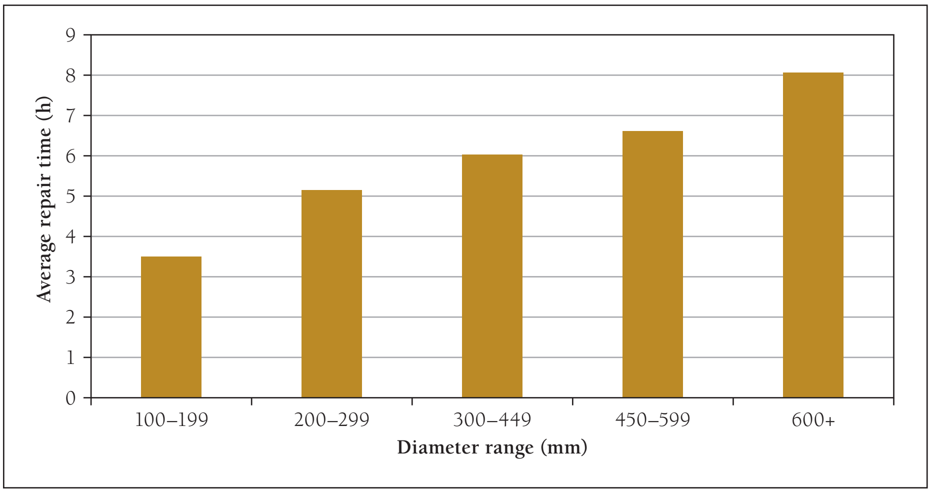

Figure 3 Average failure duration of Johannesburg steel pipe as a function of pipe diameter (from Van der Mey 1995)

System description

The Yeoville system layout is shown schematically in figure 1. Water is supplied from a connection to an independent bulk supplier and is transported to a group of three reservoirs with a total storage capacity of 106 Mℓ. The Yeoville system supplies an area of approximately 25,6 km^2, which consists of a part of the central business district of Johannesburg, light industries and both high and low density residential areas. Water is transported from the source to the reservoir complex through a single 900 mm diameter pipe with a length of approximately 1 700 m, and then through two parallel pipes (one consisting of 900 mm and 650 mm diameter sections, and the other with a diameter of 600 mm) with lengths of approximately 3 300 m.

Input parameters

Input models for the Yeoville system were developed based on available data on the Johannesburg water supply system. Measured data was used to estimate the annual average daily demand (AADD = 1 194 ℓ/s) and demand patterns. Other demand parameters were estimated from measured data of other areas in Johannesburg (Nel & Haarhoff 1996). A reasonably flat day-of-week pattern with minimum and maximum factors of 0,97 and 1,02 respectively was used. The seasonal variation was modelled on a monthly basis with minimum and maximum factors of 0,94 and 1,07 respectively. A one day auto-correlation coefficient of 0,58 and a random component with a normal distribution and standard deviation of 85 % were applied to model the average daily consumption.

Van der Mey (1995) analysed pipe failure patterns for pipes of 100 mm diameter and larger in Johannesburg from 1992 to 1994. Failure rates and repair times were estimated from detailed maintenance records held by the municipality. The study showed a clear link between pipe diameter and both failure rate and repair time as illustrated in figures 2 and 3. Repair durations were found to follow log-normal distributions with standard deviations of approximately 14 % of the average repair time.

Van Zyl and Haarhoff (1997) published a study on large fires (requiring more than 5 kℓ to extinguish) in Johannesburg for the period 1980 to 1991. They found that the occurrence of large fires is roughly once per month in the Johannesburg area. Both fire duration and fire demand follow log-

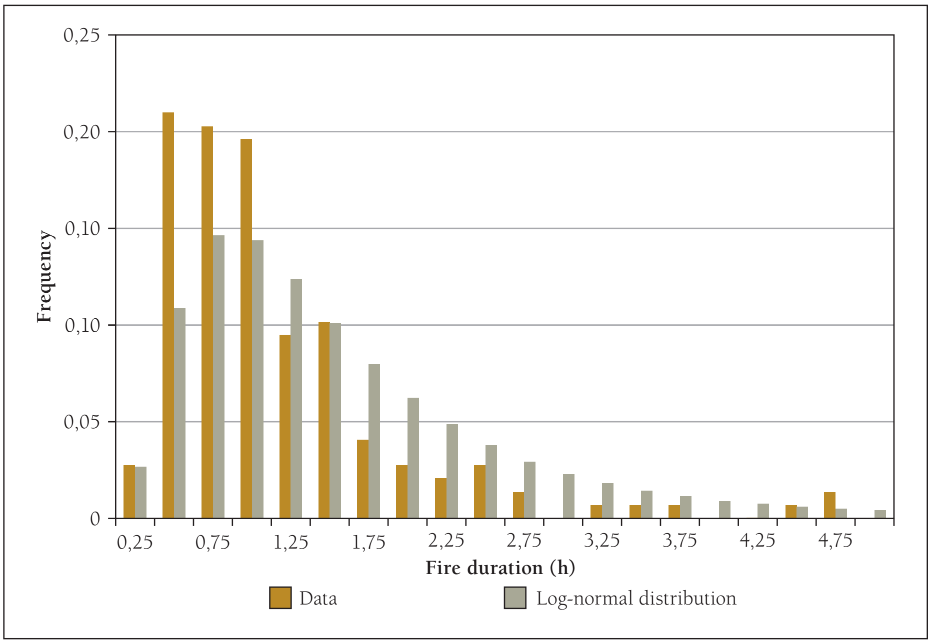

Figure 4 Large fire duration distribution in Johannesburg 1980 to 1991 (from Van Zyl and Haarhoff 1997)

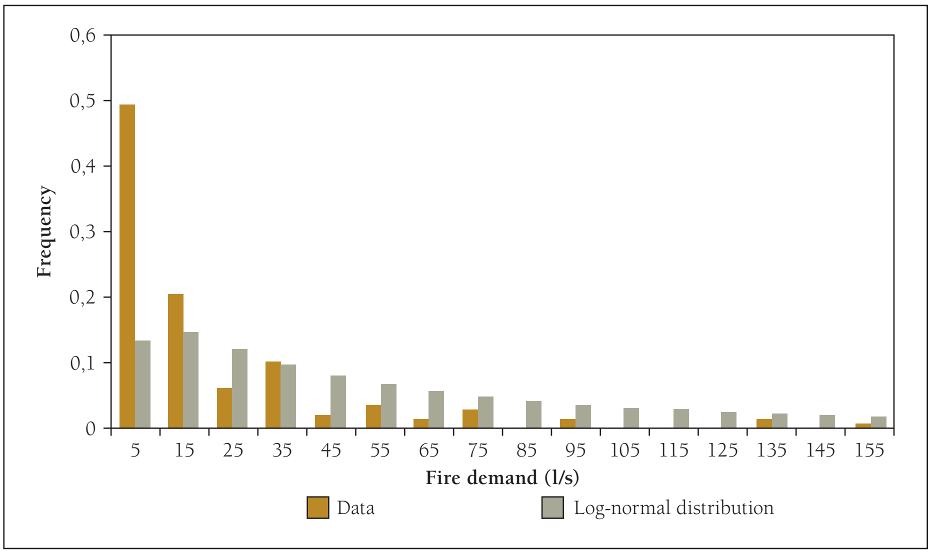

Figure 5 Large fire demand distribution in Johannesburg 1980 to 1991 (from Van Zyl and Haarhoff1997)

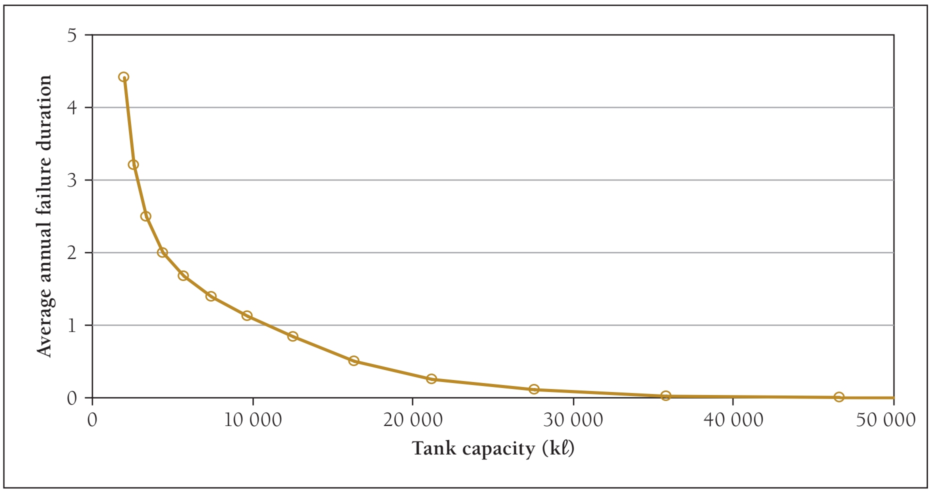

Figure 6 Average annual tank failure duration as a function of reservoir capacity

normal distributions, as shown in figures 4 and 5. Averages and standard deviations for the distributions are 0,84 h and 1,93 h respectively for the fire duration, and 10,1 ℓ/s and 3,7 ℓ/s respectively for the fire demand.

To analyse the reservoir reliability, the three reservoirs were modelled as a single storage reservoir. The reservoirs were assumed to be two thirds full throughout the simulation and no failures were modelled on the delivery side of the reservoirs. These assumptions are conservative, since the inflow into the reservoirs will be higher once their levels reduce below the assumed level, and the maximum demand from the reservoirs is assured by not allowing failures on the downstream side of the reservoir. The supply pipe flow rate under these conditions was 1 411 ℓ/s or 1,2 times the AADD.

Results and discussion

The main aim of the case study was to investigate the reliability of the Yeoville reservoirs under various conditions. Various performance measures were calculated for the different reservoir capacities, including the number of failures, the average and standard deviation of the failure, and the maximum fail time. In this paper, the average fail time per year is used, since it incorporates two of the failure parameters: the average number of failures per annum and the average failure duration.

A sensitivity analysis with different simulation durations showed that the results converged fairly quickly and a simulation of 500 years in hourly steps was found to give reliable results. Figure 6 shows the relationship between the annual average fail time and reservoir capacity for the Yeoville system. The figure gives a quantitative estimate of the reliability of the system for different reservoir capacities. For instance, if on average one hour per year down time is used as an acceptable level of service, the figure indicates that a reservoir capacity of approximately 10,9 Mℓ, or 2,5 h of annual average daily demand (AADD), is required.

The detailed results show that a 10,9 Mℓ reservoir would on average fail once every four years with an average failure duration of four hours. For reservoir capacities of 20 Mℓ (4,7 h AADD) and 30 Mℓ (7 h AADD), the average down times are 18 minutes per annum (2,2 hours every 7,3 years) and 5 minutes per annum (1,2 hours every 14,5 years) respectively. This increase in reliability is partly due to a reduction in the average failure duration, but mainly due to a significant reduction in the failure frequency. It is clear that the current reservoir capacity of 106 Mℓ will provide a high level of reliability although at 25 hours of AADD it is considerably smaller than the South African design guideline requirement of 48 hours of AADD.

A further application of stochastic analysis is that it can be used to compare different scenarios to find the optimal pipe and reservoir configuration for a particular system. In figure 7 the reservoir reliability curves are shown for a number of different supply pipe configurations. First, the two parallel pipes were replaced with a single pipe of equivalent diameter. This system is more vulnerable than the parallel pipe option, since a failure in any section of the single pipe will prevent any water from reaching the reservoirs. The figure shows

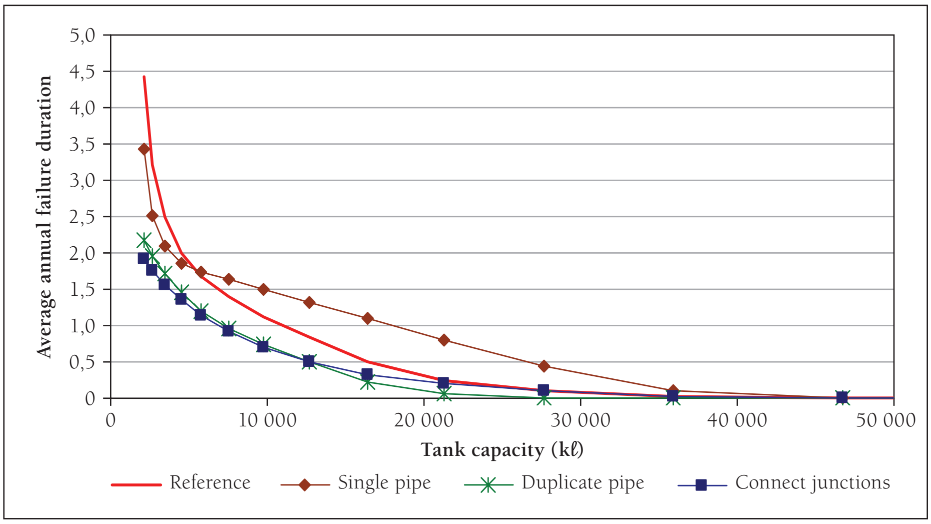

Figure 7 Average annual failure duration relationships for different supply pipe configurations

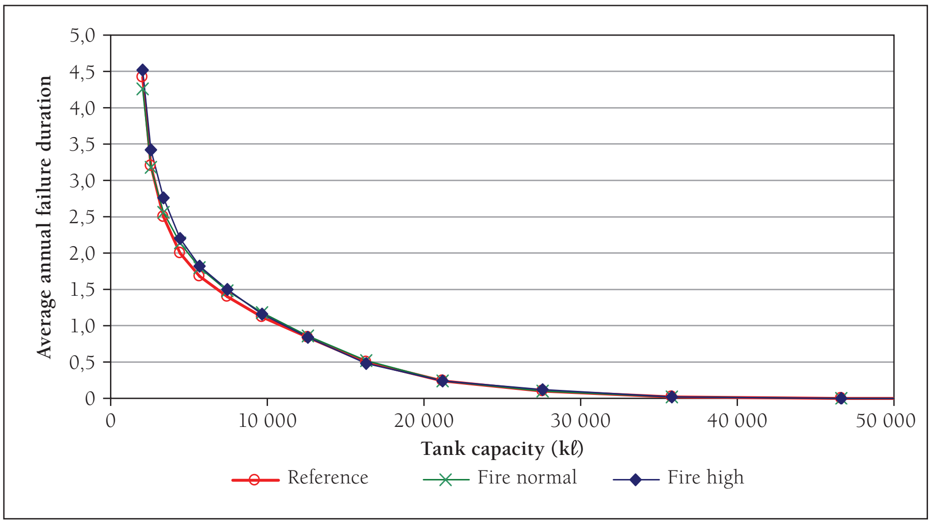

Figure 8 Average annual failure duration relationships for different fire water models

that to obtain a reliability level of one hour average fail time per year, a reservoir with a capacity of approximately 17 Mℓ (4 h AADD) is required, which is substantially larger than the parallel pipe case.

Two changes to the supply pipe configuration were tested in an attempt to improve the reservoir reliability. In the first change, an 820 m section of 900 mm diameter pipe was added in parallel with the single section of the pipe near the source. This not only improved the reliability of the supply pipe system, but also increased the supply capacity to the reservoirs by 7,3 %. In the second change, a short section of pipe was used to link the two parallel pipes roughly halfway along their lengths. This increases the inherent reliability of the supply pipe by allowing a smaller length of the pipe to be isolated when a failure occurs. The results of the analyses show that the two changes produce virtually identical improvements in the reliability of the system. Considering that interconnecting the two parallel pipes will be substantially cheaper than adding a parallel pipe section, it is clearly the preferred option.

A final analysis was done to demonstrate the effect of fire demand on the required reservoir capacity. It was conservatively estimated that one third of fires in the Johannesburg area will occur in the Yeoville supply zone. A high fire scenario was also run by increasing the average fire duration to 1,7 hours and the average fire demand to 107 ℓ/s. The results (figure 8) show that neither of the fire scenarios had a significant effect on the reservoir reliability. This is in contrast with the South African design guidelines that require up to 4,3 Mℓ additional storage capacity for fire only. The reason for this most probably lies in the fact that it is very unlikely that a fire will occur at the same time that both the balancing and emergency storage components of the reservoirs are exhausted.

CONCLUSIONS

A method for the reliability analysis of municipal storage reservoirs through stochastic analysis is proposed and applied in a case study. The method includes stochastic models for water demand, pipe failures and fire events and allows the relationship between reservoir capacity and reliability to be quantified.

The stochastic method was applied to analyse the reliability of the Yeoville reservoirs in Johannesburg. The results show the reservoir reliability to be good, even though it is significantly smaller than the South African design guidelines require. It is also shown that fires do not significantly affect the reliability of a reservoir indicating that design guidelines that require all fire water to be added to the reservoir capacity may be overly conservative.

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