Optimal Reliability-Based Design of Bulk Water Supply Systems

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Abstract: The hydraulic reliability of bulk water-supply systems can be defined in terms of the failure frequency of the municipal storage tanks they supply: the system fails when the tank runs dry and is functional otherwise. Municipal storage tanks are normally sized according to deterministic guidelines that make allowances for balancing, fire and emergency storage. In this study, genetic algorithm (GA) optimization was used together with stochastic analyses to find the optimal combination of feeder pipe configuration, feeder pipe capacity and tank capacity for a given risk of failure. A sensitivity analysis was conducted to determine the factors that have the greatest impact on the optimal design for an example system. The results showed that the optimal pipe configuration is a single feeder pipe in most cases, but that two parallel pipes are preferable for shorter feeder pipes. It was found that it is often cost-effective to trade off a smaller tank size for a greater feeder pipe capacity. Based on this finding, design guidelines are likely to specify suboptimal solutions in many cases. **DOI: 10.1061/(ASCE)WR.1943-5452.0000296.** © *2014 American Society of Civil Engineers.*

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Introduction

Bulk water-supply systems are usually designed according to deterministic guidelines that specify minimum tank, and sometimes feeder pipe, design capacities. Since design guidelines have to accommodate a large range of possible conditions, they invariably have to adopt a conservative approach, meaning that most systems are potentially overdesigned. Design guidelines cannot take local conditions into account, and do not give the designer much leeway, for instance to use a smaller tank in a system with a short, high capacity feeder pipe.

Reliability of engineering systems can be broadly defined as the probability that a system performs its mission within specified limits for a given period of time in a specified environment (Cullinane et al. 1992). Farmani et al. (2005) define the reliability of water distribution systems as the ability of the network to provide consumers with adequate and high-quality supply even under abnormal conditions. Alternatively, reliability can be defined in terms of network failure, which is an event in which the network is unable to provide adequate flow or pressure to meet demand (Goulter 1992). More specifically, the reliability of a bulk water-supply system can be defined in terms of the reliability of its storage tank, as consumers will only notice a service interruption if the storage tank has failed (i.e., run dry).

Various authors have analyzed the reliability of bulk water-supply systems using frequency duration (Hobbs and Beim 1988), Markov chain (Beim and Hobbs 1988) and Monte Carlo (Beim and Hobbs 1988; Nel and Haarhoff 1996) approaches. van Zyl et al. (2008) used a Monte Carlo analysis model in combination with three generic models for consumer demand, fire water demand, and feeder pipe failures to estimate the failure characteristics of bulk supply systems, and proposed a reliability-based design criterion of one failure in 10 years under seasonal peak conditions. The stochastic model has also been used to explore the impact of different water demand parameters on system reliability (van Zyl et al. 2012).

A major benefit of a risk-based design criterion for bulk supply systems is that the designer can size system components to suit local conditions, and trade off different components (e.g., feeder pipe and tank capacities) to find the most cost-effective solution. The aim of this study was to develop a method to investigate the Pareto-optimal trade-off curve between the failure frequency and cost of a bulk supply system. This curve can then be used by a designer to select the most cost-effective system that satisfies the minimum reliability requirement (i.e., maximum failure frequency) of a given application. The design variables considered in the analyses were storage-tank capacity, feeder-pipe diameter, and feeder-pipe configuration. Although the proposed method is illustrated using a simple bulk system layout consisting of a tank connected to a source via a feeder pipe, it can also be applied to more sophisticated systems.

The next section in the paper describes the methodology used to estimate the optimal trade-off curve between system failure frequency and cost. This is followed by a discussion of the application of the model to a simple, but typical bulk supply system. A sensitivity analysis of various system and stochastic parameters is then presented, giving insight into how these factors affect the optimal design of bulk supply systems. Finally, conclusions are drawn based on the application of the model and the sensitivity analyses.

Methodology

Optimization Model

The aim of the optimization was to minimize the cost and failure frequency (maximize reliability) of a bulk water-supply system by

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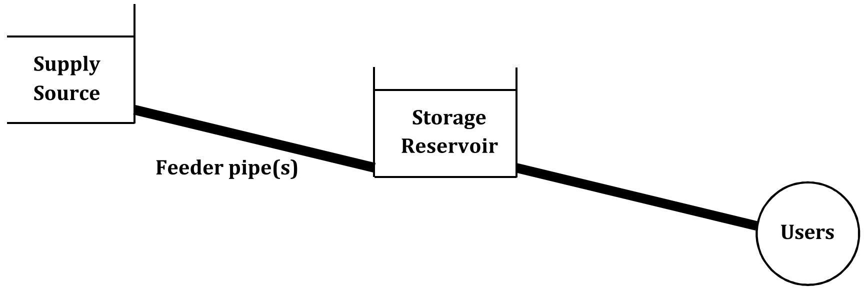

Fig. 1. Example system layout

selecting optimal combinations of tank capacity, feeder pipe configuration and feeder pipe diameter. To illustrate the methodology followed, a simple yet frequently used supply system configuration (Fig. 1) was used. The system consists of a source, storage tank and feeder pipe(s) between the source and tank. Users are supplied from a separate pipeline connected to the tank.

There are three decision variables in this optimization problem: feeder pipe configuration, feeder pipe diameter, and tank capacity. Three parallel pipe options (1 pipe, 2 parallel pipes, or 3 parallel pipes) and three interconnection options (0, 1, or 2) exist. Feeder pipe sizes were limited to commercially available diameters. User-defined upper and lower bounds were used for the pipe diameter to exclude unrealistic options. Finally, the tank capacity was modeled as a continuous variable between upper and lower bounds selected by the designer.

A gravity system was considered in this study. Thus assuming that the designer has already selected a location for the source and the tank, the system head (difference in elevation) and the length of the feeder pipe system was considered known. The flow rate between the source and the tank was calculated using the Hazen-Williams equation for each combination of pipe configuration and diameters.

The flow rate can be expressed as a dimensionless supply ratio, defined as the feeder pipe capacity over the average demand for the period modeled (typically one week). In this study simulations were done under seasonal peak demand conditions. The range of supply ratios investigated was limited between a lower bound of one and a user-defined upper bound. A supply ratio less than one means that the source feeder pipes cannot supply the average demand and thus the system is infeasible. On the other hand, the highest supply ratios are obtained when the largest diameters are used in a configuration of three pipes in parallel. At some supply ratio, these combinations become too expensive to be feasible, and thus can be excluded from the solution space.

The lower and upper bound supply ratios were used as a guide to determine which pipe diameters would be feasible and retained for selection in the optimization run. This resulted in the use of the following two conditions where a diameter was eliminated if: (1) the supply ratio for a single pipeline was greater than the upper bound, or (2) the supply ratio was less than one for three parallel pipes.

The multiobjective genetic algorithm (GA), NSGA-II (Deb et al. 2002), was used to find the optimal solutions and produce the Pareto-optimal trade-off curve between the conflicting objectives of minimizing system cost and minimizing tank failure frequency. In NSGA-II, the initial population is generated, followed by an evaluation of the objective functions using a cost model and stochastic analysis method. Until the maximum number of generations is reached, the algorithm loops through the process of generating a parent, ranking the population, performing comparison and selection based on nondomination and crowding distance to finally generate a child population. The Pareto-optimal set was taken as the child population produced in the final generation of the algorithm.

Genetic algorithms require a large number of system evaluations, and since each evaluation requires a computationally expensive stochastic analysis, the duration of a typical optimization run was found to be impractically long (approximately 270 h for 50 generations and a population of 50). To reduce the simulation time, a compression heuristic was implemented that fully simulated periods where pipe failure or fire events occurred, but *jumped over* intermediate periods. This allowed the duration of an optimization run to be reduced by 75% to a manageable 66 h.

Cost Model

The cost model used in this optimization process considered capital costs only. The costs of components relative to each other are critical for the analysis, rather than the absolute cost values. Cost functions for pipes and storage tanks were based on the models described by Swamee and Sharma (2008). The pipe cost function was

$$C_p = 324LD^{0.933} \tag{1}$$

where C_p = pipe cost (\$), L = pipe length (m), and D = pipe diameter (m).

The cost function used for a surface concrete tank was

$$C_R = \frac{196V_R}{[1 + (\frac{V_R}{1100})^{5.6}]^{0.075}} \tag{2}$$

where C_R = service tank cost (\$), and V_R = volume of the tank (m^3).

Various pipe configurations were considered, which included interconnections between pipes in parallel including valve chambers and shut-off valves on all branches. Chambers are required to house the necessary valves and pipework. Vlok (2010) developed an equation to represent the chamber costs, which were adjusted to the same financial basis. For the interconnection of two pipes, the cost function of a single chamber, including pipework and valves was

$$C_c = 0.0309D^2 + 11.161D + 1773 \tag{3}$$

and the cost function of a chamber for the interconnection of three pipes is

$$C_c = 0.0473D^2 + 16.823D + 1885.3 \tag{4}$$

where C_c = cost of the chamber (\$), and D = pipe diameter (mm).

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Stochastic Analysis Model

The stochastic analysis model (van Zyl et al. 2008) measures the reliability of each solution determined during the optimization run by estimating its tank failure frequency.

The stochastic analysis method consists of three stochastic unit models for consumer demands, fire demands and pipe failures. The method involves calculating the consumer and fire demand, and supply inflow to the tank for each hourly time step using Monte Carlo sampling, which are then used to update tank levels. If the tank runs dry, a failure is recorded and the results are logged. This process is repeated until either: (1) 5% convergence has been obtained for the failure frequency results; (2) the failure frequency is less than a minimum failure rate specified by the designer (e.g., one failure in 100 years); or (3) the run duration exceeds that which is specified by the designer. To give an idea of a typical value for condition 3, a run duration of two million days was used in the example system.

In the optimization run, the stochastic analysis was done for the most critical time in the year, i.e., under seasonal peak conditions. An important assumption of the stochastic analysis is that it is done at a specific time, typically a week, in the year and design horizon, meaning that long-term and seasonal variations in parameters are not included in the simulation run. Simulations can be repeated at different times in the year and design horizon to consider these variations.

Consumer Demand

Consumer demand was modeled using a generic demand model consisting of an average demand, day-of-week and hourly patterns, persistence and a random component. First, the average daily demand is calculated, which is then used to calculate the hourly demands. A multiplicative model models the cyclical patterns and the remainder corresponds to an autocorrelated random process. The daily demand model is

$$D_d = D_{\text{ave}} \cdot C_{\text{DOW}} \cdot \upsilon_d \tag{5}$$

where D_d = simulated average demand in day d, D_{ave} = average demand for the period studied, C_{DOW} is a day-of-week demand factor, and υ_d = daily demand residual function, described by

$$\ln \upsilon_d = \sum_{i=1}^{m} \phi_i \ln \upsilon_{d-i} + \ln \varepsilon_d; \qquad \ln \varepsilon_d \sim IN(0, \sigma_D^2) \tag{6}$$

where i is a lag counter, m the number of daily autocorrelation lags, ϕ_i the daily auto regression coefficient for lag i and $\ln \varepsilon_d$ a white-noise process. The notation $\ln \varepsilon_d \sim IN(0, \sigma_D^2)$ indicates that the natural logarithms of the residuals are normally and independently distributed with mean 0 and variance σ_D^2.

Autocorrelation is used to describe the persistence inherent in the data, i.e., how much the demand of a current period is affected by previous periods. Both daily and hourly levels of persistence were included.

A similar model is used to model the hourly demand variation

$$D_h = D_d \cdot C_h \cdot \upsilon_h \tag{7}$$

where D_h is the average demand for hour h, D_d is the average demand for the current day, C_h is the hourly demand factor and υ_h is the hourly demand residual function, described with a similar equation as the daily demand residuals.

Fire Demand

The fire demand model consists of three generic components: occurrence, duration, and fire flow. Fire events were modeled by simulating the times between successive fires using an exponential distribution. The probability density function of an exponential distribution is

$$f(\Delta t; \lambda) = \lambda e^{-\lambda \Delta t}; \qquad \Delta t \geq 0 \tag{8}$$

where λ = rate parameter and Δt = time between successive fire events.

After a fire has occurred, the fire duration and fire flow were both estimated using log-normal distributions. For the case of fire duration, the probability density function for a log-normal distribution is

$$f(T; \mu, \sigma) = \frac{1}{T\sigma\sqrt{2\pi}} e^{-(\ln T - \mu)^2/2\sigma^2}; \qquad \Delta t \geq 0 \tag{9}$$

where T = duration of the fire event, μ = mean of the logs of the durations, and σ = standard deviation of the logs of the durations.

Pipe Failures

Failures of the water source, purification tanks, pumps and pipes can all cause the interruption of the supply inflow to the storage tank, although only pipe failures were included in this study. It was assumed that the supply was not limited by the source (i.e., only by the capacity of the pipes) and source failures were not considered.

The pipe failure model consisted of two generic components: occurrence and duration. An exponential model was used for modeling the time between failure events [Eq. (8)] and a log-normal distribution for the failure duration [Eq. (9)]. The duration of a supply system failure represents the time the supply is interrupted and normally corresponds to the time that a pipe section is isolated by the repair team.

Only one pipe failure was modeled at a time. The occurrence of two simultaneous pipe failures was not modeled as the probability of it happening is negligibly small.

Changing the configuration from a single pipe to parallel pipes increases the reliability of the bulk water-supply system (van Zyl and Haarhoff 1999). For example, for two pipes in parallel there is always 50% of the flow remaining, while for three pipes in parallel there always two thirds of the total supply capacity entering the storage tank, if one pipe failure is modeled at a time. Increasing the number of interconnections between parallel pipes further increases the reliability of the feeder pipe system. Table 1 indicates how much supply inflow remains for each configuration when a single pipe failure occurs.

Table 1. Summary of Remaining Supply Inflow to the Storage Tank as a Percentage for Each Pipe Configuration

Pipe configuration	Description	Flow capacity during failure (%)
1	Single pipe, no interconnections	0
2	2 parallel pipes, no interconnections	50.0
3	3 parallel pipes, no interconnections	66.7
4	2 parallel pipes, 1 interconnection	63.7
5	3 parallel pipes, 1 interconnection	78.7
6	2 parallel pipes, 2 interconnections	71.3
7	3 parallel pipes, 2 interconnections	84.3

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Compression Heuristic

A compression heuristic was developed to reduce the time required to run a stochastic analysis. Without this, it would have been impractical to include the stochastic analyses runs into a genetic algorithm optimization routine. In analyzing the computational effort required to perform stochastic analyses, it was observed that in most time steps, there are no fire or pipe failure events and only consumer demand plays a role. By doing a prerun to characterize the behavior of the system under consumer-demand-only conditions (i.e., no pipe failures or fire demands), it was possible to *jump over* the periods where no fire or pipe failure events were occurring, thus speeding up the simulation substantially.

The compression heuristic fully simulates the critical periods during which fire and pipe failure events occur in an events run, and constrains the simulation of the consumer demand only behavior to a prerun. The prerun computes discrete failure frequency results for a preset table of supply ratios and tank capacities, which are independent of the component sizes for the trial solutions in the events run. When a trial solution is analyzed in the events run, its demands failure frequency is looked up from the table (using interpolation where necessary), and is combined with the events failure frequency calculated from the events run, to obtain the total failure frequency of the system. The total failure frequency is used as a measure of the system reliability.

Trade-Off between Reliability and Cost

The optimization model was applied to a single bulk water-supply system to produce a Pareto-optimal trade-off curve of solutions based on failure frequency and cost. It was applied to an example system with the configuration shown in Fig. 1.

This example system is described in detail in van Zyl et al. (2008), and thus only the most important parameters are provided here. The system was analyzed under seasonal peak conditions, representing the most critical time of the year. The demand model of the system was based on three small towns in France and the demand pattern had a seasonal peak factor of 1.49. The system has an average demand of 80 l/s, head difference of 60 m between the source and tank, feeder pipe length of 10 km and a Hazen-Williams flow coefficient of 120. A fire frequency of six fires/annum and pipe failure rate of 0.2 failures/km/annum were used.

The aim of the optimization was to find the trade-off curve between reliability and cost by finding the optimal combinations of pipe configuration and size, and tank capacity. Seven pipe configuration options were allowed, ranging from one pipeline to three pipes in parallel, with up to two equally spaced interconnections between parallel pipes (Table 1). Feasible pipe diameters of 227, 286, 322, and 363 mm were determined from the range of commercially available pipe sizes (Raad 2010). Lower and upper bound supply ratio values of 1.0 and 2.0, respectively, were used. The resulting supply ratios for each practical combination of pipe configuration and diameter are summarized in Table 2. The range of the tank capacity was selected to be 4–16 h of seasonal peak demand for this example system. This range of tank capacities is fairly narrow so as to reduce the solution space. However, it was relaxed to allow larger tanks in if the optimization routine initially selected the maximum allowed tank capacity.

The multiobjective optimization was carried out for 50 generations for a population size of 50 solutions, which took approximately 69 h on a 2.66 GHz Intel Core 2 Quad processor. The resulting trade-off curve between failure frequency and cost is shown in Fig. 2, ranging from low reliability, low-cost solutions on the left of the curve to high reliability, high-cost solutions on the right. A more detailed view of solutions with a failure rate below one failure in eight years is given in Fig. 3.

The leftmost solution in Fig. 2 has the lowest cost of $1,022,800. This was obtained through the selection of the smallest possible tank capacity of 4 h of seasonal peak demand and a single 227-mm diameter pipeline, resulting in a supply ratio of 0.53. Thus, the low cost was achieved at the expense of the reliability of the solution, as it has a high failure frequency of 357 failures/annum, roughly equivalent to one failure per day as can be expected for an obviously infeasible supply ratio lower than 1.

Distinct gaps are visible in the trade-off curve and are attributed to the discrete nature of the optimization problem. Minor gaps

Table 2. Supply Ratios for Different Combinations of Pipe Configuration and Diameter

	Configuration		
Diameter (m)	1 pipe	2 pipes	3 pipes
0.227	0.5330	1.0660	1.5990
0.286	0.9787	1.9573	2.9360
0.322	1.3367	2.6735	4.0102
0.363	1.8321	3.6641	5.4962

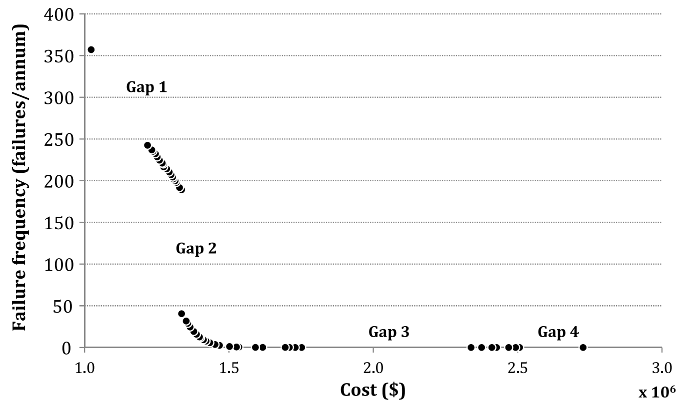

Fig. 2. Trade-off curve of optimal solutions for the test system (under seasonal peak conditions)

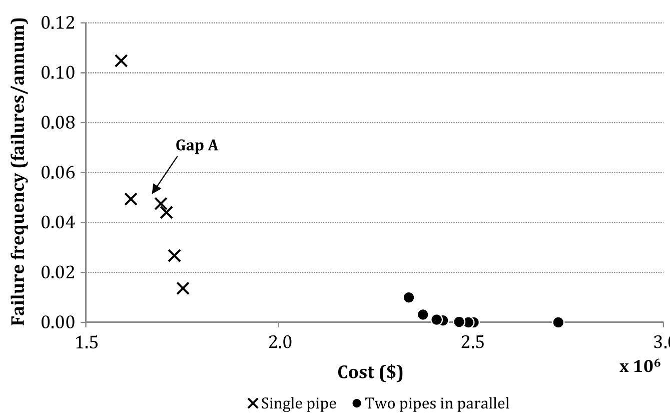

Fig. 3. Trade-off curve of optimal solutions for the example system with less than one failure in eight years

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between solutions simply represent changes in the tank size, whereas the major gaps between solutions are caused by a discrete change in the number of parallel pipes or pipe diameter. In Fig. 2, Gaps 1, 2, and 4 represent increases in pipe diameter, i.e., an increase in supply ratio. For example, the solution to the left of the second major gap has a single 286-mm diameter pipeline with a 0.98 supply ratio, while the solution to the right of the major gap has a single 323-mm diameter pipeline with a supply ratio of 1.34. It is evident that increasing the supply ratio significantly improves the reliability of the system. Similarly, an increased pipe diameter increases the system cost.

The cost of a pipeline is a function of its diameter so a clear trend of increasing cost with increasing pipe diameter is evident. In addition, the cost of pipelines increases with length, which means that two parallel pipes are double the cost of a single pipeline with the same diameter, assuming that the pipes are laid in separate trenches. As a result, there is a third distinct gap (Gap 3) in the trade-off curve because of the change in pipe configuration from a single pipeline to two parallel pipes, i.e., there is a sudden increase in cost from \$1.75 to \$2.34 million. For the example system, the majority of solutions in the trade-off curve, and all solutions below \$1.8 million, use a single pipeline instead of parallel pipes.

Looking more closely at Fig. 3, Gap A illustrates the effect of increasing the diameter of a single pipeline from 322 to 363 mm, and decreasing the tank capacity from 15.9 to 13.0 h. By increasing the diameter and thereby the supply ratio from 1.34 to 1.83, and decreasing the tank capacity, the improvement in reliability is marginal (0.049 to 0.048 failures/annum), whereas an increase in total system cost is proportionally much greater.

Systems with single pipelines generally have a lower reliability than systems using parallel pipes. However, for the example system, solutions with single pipelines were able to meet the desired reliability criterion at substantially lower cost, as illustrated by the crosses in Fig. 3. The solution closest to the desired reliability of 0.1 failures/annum consists (with failure frequency of 0.1048 failures/annum) of a single pipeline of diameter 322 mm, supply ratio at seasonal peak demand of 1.34, tank capacity of 14.5 h of seasonal peak demand and a cost of \$1.59 million.

It was found that parallel pipe systems are more reliable, yet significantly more expensive than single pipe systems as shown in Fig. 3. The parallel pipe systems (shown with circles) all consist of two pipes in parallel. No systems with three pipes in parallel were present in the final solution set. Pipes in parallel provide additional reliability to the system, as at least half the supply into the tank remains when there is a pipe outage. The optimal tank sizes for these solutions are notably smaller than for systems with single pipe configurations.

The rightmost solution in the trade-off curve represents the most reliable, yet most expensive system at \$2.73 million. It consists of two pipes in parallel and no interconnections, with the largest available pipe diameter of 363 mm, but with the smallest allowable tank capacity of 4 h of seasonal peak demand. Since the inflow capacity is 3.66 times greater than the seasonal peak, the storage tank experiences a negligibly small number of failures. The high cost of the system can be attributed to the fact that the feeder pipe consists of two 363-mm diameter pipes in parallel, which contributes to 92% of the total system cost. It is nearly 12 times the cost of the storage tank.

For the example system with a feeder pipe length of 10 km between the source and the tank, the cost of the feeder pipes were found to make up 70–90% of the total cost of the system.

Sensitivity Analysis

Sensitivity Parameters and Trade-Off Curves

A sensitivity analysis was conducted on the example system varying certain individual system (supply pipe length and system head) and stochastic parameters (peak hourly demand, fire rate, pipe failure rate, and failure duration) between low and high values. Low and high values were selected based on literature and accepted values in practice. The low, typical and high values for each parameter are summarized in Table 3.

For each parameter the optimal trade-off curves for high and low values could be compared to the base system by plotting them on a single set of axes. As an example, the trade-off curves for the available head parameters are shown in Fig. 4. The available head has a significant effect on the design, since a higher available head means that more energy is available for friction pipe losses and thus smaller diameters can be used. Thus the figure shows that the trade-off curve for the 30-m head system shifted to the right and the curve for the 120-m head system shifted to the left of the curve for the typical system.

Impact on Optimal Design

To allow a comparison of all the sensitivity analysis runs, a design system was selected based on the solution closest to a failure rate of one failure in 10 years under seasonal peak conditions. These solutions are summarized in Table 4.

The cost and reliability of existing design guidelines are included in Table 4. It was assumed that the system is designed for a 20-year design horizon, and that the water demand grows at 3% per annum. Thus the water-supply system is designed to handle a demand of 80 l/s in 20 years' time, and the *current* average demand can be calculated back as 44.3 l/s.

Table 3. Sensitivity Analysis Parameters

Sensitivity parameter	Low	Typical	High
Length (km)	1	10	100
Available head (m)	30	60	120
Hourly demand pattern: Peak factor	1.25	1.49	1.75
Fire rate (fires/annum)	0	6	24
Pipe failure rate (failure/km/annum)	0.1	0.2	0.5
Average failure duration (h)	3	4.5	9

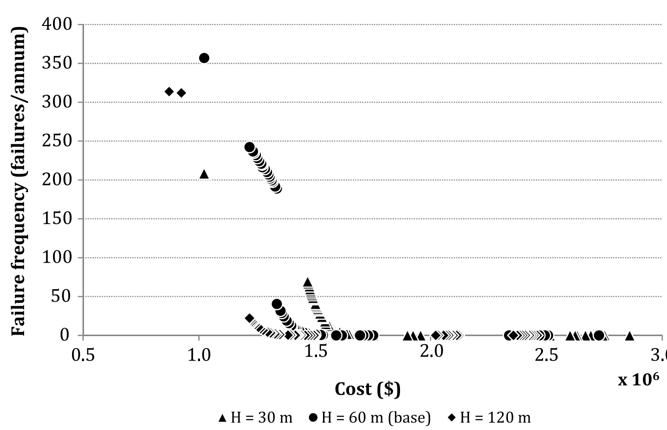

Fig. 4. Trade-off curves for systems with different heads

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Table 4. Near Optimal Solutions Satisfying Design Criterion for Each Sensitivity Parameter

Description	Number of pipes	Feeder pipe diameter (mm)	Supply ratio	Tank capacity (h)	Capital cost ($)	Failure frequency (failures/annum)[a]	Comment
Base	1/0	322	1.34	14.5	1,592,064	0.1048	Typical system and stochastic parameters
Length—low	2/0	182	2.07	4.1	347,101	0.0664	L = 1 km
Length—high	1/0	574	1.76	18.0	19,829,228	0.0954	L = 100 km
Head—low	1/0	363	1.26	16.0	1,752,161	0.1030	H = 30 m
Head—high	1/0	286	1.42	13.7	1,458,424	0.0829	H = 120 m
Demand—low	1/0	322	1.34	12.1	1,545,695	0.0952	Hourly peak factor = 1.25
Demand—high	1/0	363	1.83	14.0	1,715,773	0.0744	Hourly peak factor = 1.75
Fire rate—low	1/0	322	1.34	14.5	1,590,506	0.1056	No fires
Fire rate—high	1/0	322	1.34	14.0	1,618,858	0.1079	Fire rate = 24 fires/annum
Pipe failure rate—low	1/0	322	1.34	13.6	1,575,040	0.1068	Failure rate = 0.1 failures/km/annum
Pipe failure rate—high	1/0	363	1.83	13.5	1,705,892	0.1026	Failure rate = 0.5 failures/km/annum
Failure duration—low	1/0	322	1.34	13.5	1,571,882	0.0945	Average failure duration = 3 h
Failure duration—high	1/0	363	1.83	21.5	1,844,648	0.0980	Average failure duration = 9 h
U.S. guidelines	1/0	303	1.14	35.0	1,840,992	0.0006	—
SA guidelines	1/0	289	1.01	32.0	1,755,589	0.3100	—

[a]The solutions selected are those with failure rates closest to one failure in 10 years.

A typical tank size for residential areas in the United States is 52 h of annual average daily demand (AADD) (van Zyl et al. 2008), or 35 h seasonal of peak demand for the example system. It was assumed that the feeder pipe is sized for the peak day of the year and a 20-year design horizon, i.e., 1.14 times the seasonal peak demand at the end of the design horizon. Assuming a continuous range of pipe sizes to get the theoretical minimum feeder pipe diameter gives a single 303-mm pipe. Stochastic analysis of this system at the design horizon resulted in a very reliable system with a failure frequency of 0.0006 failures/annum (1 failure every 1,700 years) under seasonal peak conditions, at a cost of $1,840,992.

South African design guidelines specify that the capacity of the feeder pipe should be at least 1.5 times AADD (essentially equal to seasonal peak demand for the example system), and the tank capacity should be 49 h of AADD (i.e., 32 h of seasonal peak demand) (van Zyl et al. 2008). If the system was designed according to these guidelines, it would then require a theoretical 289-mm diameter feeder pipe. A system satisfying these requirements at the design horizon has a cost of $1,755,589 and an unacceptably high failure frequency of 57 failures/annum under seasonal peak conditions.

These examples show how design guidelines may result in overly expensive and sometimes even unreliable systems. It is recognized that tanks that are designed according to these guidelines do not fail all the time in practice. An explanation for this is that failure frequency is highly sensitive to the supply ratio (van Zyl et al. 2012), thus for the rest of the year where seasonal demand is lower, the tank is very reliable. The same goes for early performance in a long design horizon.

Cost Comparison of Optimal Systems

Fig. 5 illustrates the proportions contributed by the individual system components to the total cost for each optimal solution. Changing the system and stochastic parameters generally does not have a significant impact on the relative costs. The feeder pipe consistently makes up approximately 70% of the total cost, with the storage tank making up the balance. The only exception is for the two solutions where the pipe length was varied. For a short pipe length, the tank cost (62% of the total) outweighs the pipe cost (38%); while in the case of the long pipe length, the pipe cost makes up nearly all (97%) of the total cost.

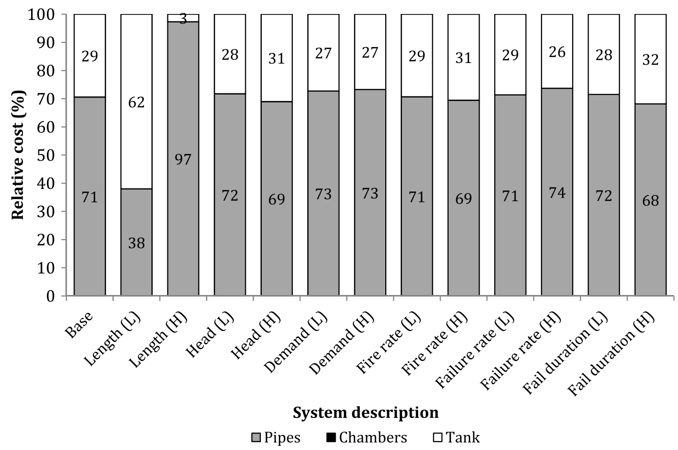

Fig. 5. Relative costs of individual components for each optimal solution

The impact that each sensitivity parameter has on the system cost is shown in a spider graph in Fig. 6. It is clear that the supply pipe length dominates the optimal solutions produced. A longer pipe length does not only result in a higher direct system cost, but also indirectly increases the system cost through a greater failure frequency on the feeder pipe. Further analysis of the pipe length results showed that a bulk system with a short pipe length is more economical if it has a parallel pipe configuration with a small tank, whereas a system with a longer pipe length is more economical if it has a single pipe configuration and a larger tank size.

Excluding pipe length from Fig. 6 shows the effect of the other parameters more clearly in Fig. 7. Besides pipe length, the most significant factors are the available head and the average pipe failure duration. In comparison, the fire rate, pipe failure rate, and peak hourly factor have small impacts on the design. Interestingly, fire demand had the lowest impact of all the parameters.

Trade-Off between Feeder Pipe and Tank Capacities

Finally, since the vast majority of optimal solutions used a single feeder pipe, it is interesting to compare the remaining two variables

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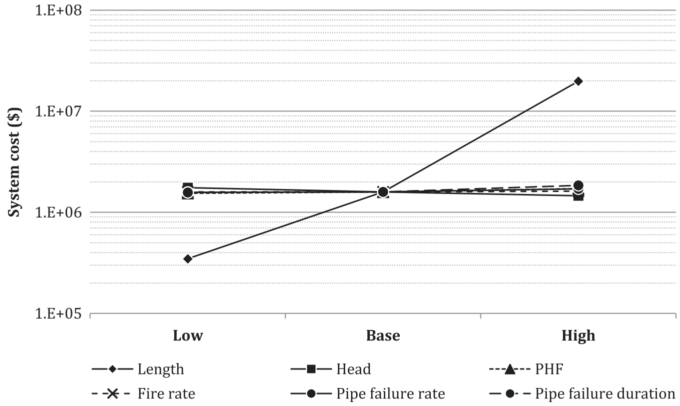

Fig. 6. Impact of sensitivity parameters on system cost

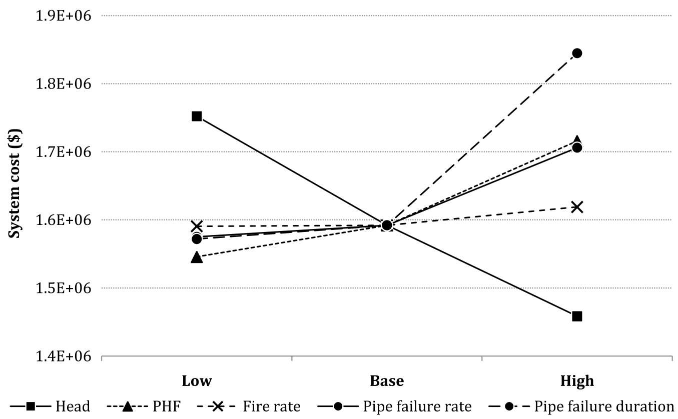

Fig. 7. Impact of sensitivity parameters (excluding length) on system cost

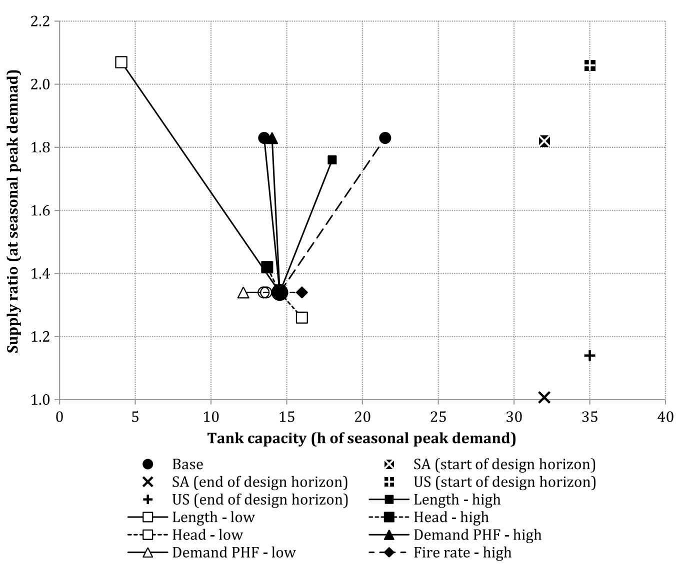

Fig. 8. Optimal combinations of supply ratio and tank capacity for different system configurations

of pipe diameter (expressed as supply ratio) and tank capacity for the design solutions as shown in Fig. 8. The results of different parameters are connected with lines to assist with reading of the graph.

An interesting feature of the figure is that the supply ratio in the optimal solutions only once drops below 1.3 (for an available head of 30 m), and then only slightly. This solution has a single 363-mm pipeline resulting in a supply ratio of 1.26 and a tank capacity of 16 h. A previous study (van Zyl et al. 2012) showed that at a supply ratio lower than 1.3, the required tank capacity and cost increase at a higher rate for the example system, which may explain the observed behavior.

At the beginning of the design horizon the supply ratios for the U.S. and South African (SA) guideline-based systems would be 2.06 and 1.82, respectively, which is significantly larger than any of the optimal solutions in the sensitivity analysis (see Fig. 8). However, by the end of the design horizon they have noticeably smaller supply ratios than the optimal solutions, while still having considerably larger storage tank capacities. This shows that conventional design guidelines may be suboptimal and that larger feeder capacities combined with smaller tanks may provide more cost-effective solutions in many cases.

Conclusions

This project dealt with the design optimization of bulk water-supply systems using a multiobjective genetic algorithm. The optimization was aimed at minimizing both cost and failure frequency (i.e., maximizing the reliability) of the bulk system by selecting the optimal combinations of tank capacity, and feeder-pipe configuration and size.

A multiobjective GA optimization technique was used to determine an optimal trade-off curve between reliability and system cost. The system reliability was defined in terms of the tank failure frequency; using a stochastic analysis technique that modeled user demand, fire demand, and feeder-pipe failure events. To allow the stochastic analyses to be included in the GA in a practical manner, a compression heuristic technique was implemented to reduce the computational effort required. The analyses were done for seasonal peak conditions, thereby estimating the reliability of the system at the most critical time in the year. It was assumed that the capacity of the supply to the tank is only limited by the feeder pipe(s), and by the capacity of the source.

The method was applied to a simple, but commonly used bulk water supply configuration to illustrate the resulting Pareto-optimal trade-off curve between system cost and reliability. A sensitivity analysis was performed to investigate the effects of changing selected model parameters to typical low and high values. Optimal designs were then selected based on an allowable failure rate of one failure in 10 years under seasonal peak conditions. The results showed that the length of the feeder pipe dominated the optimal system cost. Other factors that affected the cost of the optimal system (in order of declining importance) were the supply pipe length, available head, peak hourly factor, failure duration, failure frequency, and fire frequency. A single feeder pipe was found to be optimal, except in the case of short pipe lengths (below 1 km), where two parallel pipes with a smaller tank was found to be more cost-effective.

The results showed that it was often more economical to use a larger supply mains capacity rather than a larger tank: none of the optimal solutions for the example system had a supply ratio less than 1.26. In contrast, both the U.S. and SA design guidelines specified small supply ratios and large tanks. This indicates that conventional design guidelines may be suboptimal, and that larger feeder capacities combined with smaller tanks may provide more cost-effective solutions in many cases.

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