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# RELIABILITY ANALYSIS OF WATER DISTRIBUTION SYSTEMS

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## ABSTRACT

The major approaches to the definition and evaluation of the reliability of water distribution systems are reviewed and new insights developed. Techniques for incorporating the reliability of the sources and other sub-systems of the distribution or supply network are presented. Pressure-dependent modelling of the distribution system is shown to be invaluable if operating conditions involving a shortfall in pressure, or the severity of hydraulic failures, are to be accounted for properly. Failure tolerance and redundancy are discussed and the need for further research in this area is highlighted along with areas where there are gaps in the current knowledge. A numerical example is included.

## KEYWORDS

Water distribution systems, reliability, redundancy, pressure-dependent modelling, simulation

## 1. INTRODUCTION

There is increasing interest in techniques for evaluating the reliability of water distribution systems (WDS) partly because of a growing awareness of the need to incorporate reliability in WDS design optimisation procedures. It is well known that the process of optimising the design of WDSs also eliminates redundancy and thus potentially compromises the reliability of the system. It is recognised (BSI, 1986) that reliability can be improved by duplicating less reliable components or components the failure of which could result in serious consequences. The term "fault tolerance" is thus shown to be linked to the concept of "redundancy".

"Reliability is the ability of an item to perform a required function under stated conditions for a stated period of time" or "the probability that an item will operate in a prescribed fashion for a prescribed time under prescribed conditions without suffering any event predefined as a failure" (BSI, 1986). It is, therefore, important to ascertain what constitutes a failure. For WDSs this issue is not straightforward. There are three scenarios to be considered as follows:

1. The design system capacity is exceeded due to large demands (resulting from e.g. an increase in demands with time).
2. Partial system failure, due to the failure and/or unavailability of electromechanical components (e.g. pumps and pipes), which leads to a subnormal system performance.
3. A reduction in the capacity of the WDS, for example, because of a reduction in pipe diameters with age and/or an increase in pipe roughness (tuberculation, encrustation, etc.).

In Scenario 1, however large the excess demand, the flow delivered will at least be equal to the capacity of the WDS. It is proposed herein that this scenario be regarded as a case of capacity exceedance rather than a failure, under the strict definition of reliability. By contrast, each event belonging to Scenario 2 would constitute a failure. Notwithstanding this fact, the flow delivered (at adequate pressure) under these circumstances can be significant, depending on the severity of the failure. The unavailability of the vast majority of components in a WDS

of realistic size often has a localised effect, with other zones remaining more or less unaffected. Obvious exceptions would include, for example, major supply pipes. Finally, Scenario 3 is similar to Scenario 1, except that in the former the required function is not being performed satisfactorily even under normal operating conditions. Although Scenario 3 characterises a system which has "failed", it would seem counterintuitive to say that the WDS in question has a reliability of zero.

The choice to be made when quantifying the reliability of a WDS is whether the calculation is required to ascertain accurately how well the system is performing or merely to confirm that the system is sometimes unable to fully satisfy all demands and the frequency with which this occurs. If it is the latter, then, WDS reliability could be defined as the probability that there will be sufficient flow and pressure. Unfortunately, this approach would be unable to distinguish between the above-mentioned Scenarios 1 to 3. The alternative approach seeks to measure the extent to which the WDS is performing satisfactorily and, accordingly, defines reliability as the mean value of the ratio of the flow delivered to the flow required. This is the preferred measure herein, as opposed to the frequency with which demands (normal or excessive) exceed the capacity of the WDS. The aim of this paper is to assess the proposed reliability measure using pressure-dependent WDS modelling and to discuss ways of extending the analysis to more complex networks.

## 2. REVIEW OF ALTERNATIVE RELIABILITY EVALUATION METHODS

As mentioned previously, the probability of sufficient supply and pressure (e.g. Bao and Mays, 1990) is in reality a measure of the frequency with which the capacity of the WDS is exceeded. Cullinane et al. (1992) pointed out that it is more realistic to use a formulation which can distinguish between a range of degrees of shortfall in the flow supplied. Computationally, the approaches to WDS reliability evaluation include Monte Carlo simulation (Bao and Mays, 1990), first order reliability method (Xu and Goulter, 1999) and minimum cut sets (Su et al., 1987). In the Monte Carlo simulation approach, system states and/or events are generated in a random fashion and the performance of the WDS is ascertained by simulation. The WDS reliability is then calculated based on the number of instances with a shortfall in supply or pressure. A weakness of Monte Carlo simulation is that it requires a very large number of WDS conditions to be simulated (see e.g. Tolson et al., 2001). The minimum cut sets technique is not easy to implement, as it is difficult to identify the minimum cut sets. A minimum cut set is a subgroup of components in a system whose members must all fail for the system as a whole to fail. Ultimately, the reliability value calculated is a measure of the probability of sufficient flow and pressure.

The first order reliability method (FORM) is an approximate method (Xu and Goulter, 1999) which is computationally demanding. Tanyimboh and Kalungi (2001) provided a detailed discussion of Xu and Goulter (1999) while a further appraisal is contained in Tolson et al. (2001) in which techniques for improving the accuracy and computational efficiency are proposed. For example, the complete FORM methodology is carried out for each node of the WDS whose reliability is required. This leads to difficulties when the reliability of the WDS as a whole is needed. The interested reader may consult Tanyimboh and Kalungi (2001), Tolson et al. (2001) or Xu and Goulter (1999).

## 3. RELIABILITY CALCULATION

In this study the reliability definition used is simplified in that the demand is assumed to be constant. As such, reliability is taken as the ratio of the time-averaged value of the flow

delivered to the flow required. This can be written as (Tanyimboh et al., 2001; Tanyimboh and Sheahan, 2002)

$$R = \frac{1}{T} \left( p(0)T(0) + \sum_{m=1}^M p(m)T(m) + \sum_{\substack{m=1 \\ \forall n>m}}^{M-1} p(m,n)T(m,n) + \dots \right) + \frac{1}{2} \left( 1 - p(0) - \sum_{m=1}^M p(m) - \sum_{\substack{m=1 \\ \forall n>m}}^{M-1} p(m,n) - \dots \right) \quad (1)$$

where  $R$  is the system reliability;  $p(0)$  is the probability that no pipe is unavailable;  $p(m)$  is the probability that only pipe  $m$  is unavailable;  $p(m, n)$  is the probability that only pipes  $m$  and  $n$  are unavailable. Similarly,  $T(0)$ ,  $T(m)$  and  $T(m, n)$  are the respective total flows supplied (i.e. sum of nodal outflows) at adequate pressure with no pipes unavailable, only pipe  $m$  unavailable, and only pipes  $m$  and  $n$  unavailable. Finally,  $M$  stands for the number of pipes while  $T$  represents the total demand (i.e. sum of nodal demands). Though similar to reliability, the term ‘availability’ generally refers to the reliability of repairable systems or components and incorporates the concept of maintainability. Several functions exist for estimating the availabilities of individual pipes (Tabesh, 1998).

It is often impracticable to include all operating conditions in the evaluation of reliability. This is compensated for by the second term of Eq. (1), which is an approximation of the amount by which the first term underestimates reliability. The second term of Eq. (1) does not require hydraulic simulation of the distribution system and, consequently, does not impose an undue computational burden. It has the added advantage that its magnitude determines whether or not the accuracy of the calculated reliability value can be improved by considering operating conditions involving more multiple unavailable components. A computationally more efficient form of Eq. (1) can be written as follows.

$$R = p(0) \left[ DSR(0) + \sum_{i=1}^{NS} \left( DSR(S_i) \prod_{m \in S_i} r_m \right) \right] + \frac{1}{2} \left[ 1 - p(0) \left( 1 + \sum_{i=1}^{NS} \left( \prod_{m \in S_i} r_m \right) \right) \right] \quad (2)$$

in which  $DSR$ , the demand satisfaction ratio, denotes the ratio of the flow delivered to the flow required for the WDS configuration shown (e.g.  $DSR(0) = T(0)/T$ ).  $S_i$  denotes the system operating condition or state  $i$ , this being a particular combination of available and unavailable pipes and  $NS$  represents the number states. Finally,

$$r_m = \frac{MTTR}{MTBF} \quad (3)$$

where  $MTTR$  is the mean time to repair and  $MTBF$  is the mean time between failures. The parameter  $r_m$  is generally small for WDSs and, consequently, the value of the  $p_i$  term in Eq. (2) decreases very rapidly as system states involving more and more unavailable components are considered. It is thus uncommon to consider cases involving more than two failed components (Su et al., 1987) and the justification for this can be seen quite clearly in Eq. (2).

It has been shown that the ability of a WDS to cope, i.e. the extent to which the demands can be satisfied, while some components are not available may be used as a measure of its redundancy (Tanyimboh, 1993; and Kalungi and Tanyimboh, 2001). This can be written as

$$FT = \frac{R - DSR(0)p(0)}{1 - p(0)} \quad (4)$$

in which  $FT$  is the redundancy (or component unavailability tolerance) of the WDS. It may be noted that the evaluation of  $FT$  is trivial if the reliability  $R$  has been calculated as the  $DSR(0)$  and  $p(0)$  will also be available from the reliability calculation. Values of reliability and failure tolerance/redundancy for all demand nodes of the WDS can be computed along with those of the entire WDS in one operation using corresponding definitions and equations.

#### 4. PRESSURE DEPENDENT WDS MODELLING

The importance of the demand satisfaction ratio (DSR) cannot be overemphasised. It is the ratio of the total flow that the WDS can actually provide to the total demand. The definition of the nodal DSR is analogous. If there is insufficient pressure to satisfy the demands at the required pressure the DSR, which can be evaluated using pressure dependent modelling, will be less than 1.0. By contrast, the conventional approach to WDS modelling often yields infeasible or misleading results (Ackley et al., 2001; Tanyimboh et al., 1999 and 2002).

Interest in the modelling of pressure-deficient WDSs is increasing and the results are promising (Ackley et al., 2001; Tabesh et al., 2002; Tahar et al., 2002). The main approaches include mathematical programming and variants of the Newton-Raphson method. The results have been validated by comparing the Newton-Raphson results to those obtained using the mathematical programming technique. Further confirmation has been obtained (Hayuti, 2002) using a technique based on EPANET 2, which is a demand-driven analysis (DDA) program (Rossman, 2000). To do this, the WDS is modelled using DDA with the nodal outflows obtained by head dependent analysis (HDA) as the demands. If the HDA results are correct, then the two sets of nodal heads will be identical. The success of the HDA research has removed a major obstacle in the reliability analysis of WDSs.

With pressure dependent modelling, the relationship between nodal heads and outflows needs to be accounted for explicitly. A feature of the Kalungi and Tanyimboh (2000) model is that it relies on the intrinsic headloss properties of the WDS as ascertained in its pressure dependent modelling process to account for the relationship between nodal heads and flows. More research is needed in this area. A relationship proposed by Wagner et al. (1988) is

$$\frac{Q_j^{avl}}{Q_j^{req}} = \left( \frac{H_j - H_j^{\min}}{H_j^{des} - H_j^{\min}} \right)^{\frac{1}{n_j}}; \quad H_j^{\min} < H_j < H_j^{des} \quad (5)$$

where  $Q_j^{avl}$  is the actual outflow at node  $j$ ;  $Q_j^{req}$  is the demand at node  $j$ ;  $H_j$  is the actual head at node  $j$ ;  $H_j^{\min}$  and  $H_j^{des}$  are, respectively, the nodal head below which there would be no outflow and above which the outflow would be equal to the demand at node  $j$ .  $Q_j^{avl}$  is set to zero if  $H_j$  is less than  $H_j^{\min}$  or 1.0 if  $H_j$  reaches  $H_j^{des}$ .

#### 5. SOURCES, PUMPS AND VALVES

Many WDS components including valves and pumps can be considered as links. Consequently, their inclusion in the analysis described in Section 3 would not pose theoretical difficulties given data on their availability (e.g. mean time to repair and mean time between failures). Pumping stations (PS) with multiple pumps can be analysed as subsystems using the formulation of Section 3. For example, for each combination of available or unavailable pumps, the overall capacity of the PS can be determined. The probability that each combination will occur can be calculated as in Section 3. Thus, for example, the probabilistic mean capacity of the PS can be computed. In subsequent use, the reliability of the PS could be defined as the probability that the required flow exceeds the available capacity. This definition, however, is rather conservative and an alternative which is consistent with that of Section 3 is the ratio of the available capacity to the required capacity at any time. More research is needed to clarify this issue.

Sources including treatment works should be analysed separately to obtain their reliability values. An attempt should also be made to calculate the joint reliability of multiple sources.

The reliability could be defined in two ways, these being the probability of sufficient supply or the fraction of the demand that is satisfied. The overall supply (S) and distribution (D) reliability is then given by

$$p(S \cap D) = p(D/S)p(S) \quad (6)$$

WDS reliability calculations are usually a special case of the above formula with the (usually implied) assumption that the supply at the sources will be available, which corresponds to a  $p(S)$  value of 1.0. Approaches based on the above formula are potentially simpler than techniques which attempt to handle the supply and distribution systems in one operation. Service reservoirs should be handled with care as they are often an integral part of the distribution system.

## 6. VARIATIONS IN DEMANDS

Probability distributions have been used to describe random variations in demands but in general the distributions are not based on water consumption data. Recent research suggests that the normal and lognormal distributions often fit water consumption data reasonably well (Khomsy et al., 1996; Surendran and Tanyimboh, 2002). However more research on these and other distributions is required. Also, existing techniques for handling diurnal and random variations are computationally intensive (Tabesh, 1998; Xu and Goulter, 1999).

## 7. NUMERICAL DEMONSTRATION

The sample network is shown in Figure 1. The elevation of the nodes is 0m while the source node has a fixed head of 90m. The residual head at the most downstream node is 20m. All pipes are 1000m long with a Hazen-Williams roughness coefficient of 130. The designs for this network, based on a range of layouts, were taken from Tanyimboh and Templeman (2000) where further details including the pipe diameters can be found. The hydraulic simulations were done using PRAAWDS (Program for the Realistic Analysis of the Availability of Water in Distribution Systems; Tahar et al., 2002). The program can handle pumps and valves and uses several assumed relationships between the pressure at a demand node and its outflow and automatically incorporates the user-specified head-outflow relationship into the system of equations for the distribution network. It was assumed that nodal demands would be fully satisfied for residual heads of 20m or more while the outflow would be zero for residual heads of zero. For intermediate values of the residual head, Eq. (5) was used. Finally, pipe availabilities were calculated using the Cullinane et al. (1992) formula. The results are shown in Figures 2 and 4 while Figure 3 shows the cost of each design so that the reliability results can be put in context. The corresponding DDA values were obtained using a technique developed by Tanyimboh and Templeman (1998).

## 8. DISCUSSION AND CONCLUSION

The DDA based technique underestimated the performance under pressure-deficient conditions. For example, the maximum difference in the reliability values is 0.14% and Figure 2 would appear to suggest that the DDA values are not sensitive enough. Figure 4 would also appear to reinforce this observation. It is worth noting that the HDA graphs (in Figure 2 especially) would appear to reflect the shape of the costs plot better. While both HDA and DDA show trends of decreasing reliability with cost, it is remarkable that HDA would appear to suggest that the cost can be reduced (in some judicious way) without necessarily compromising the failure tolerance excessively. Further HDA based research is required to evaluate the failure tolerance or redundancy parameter.

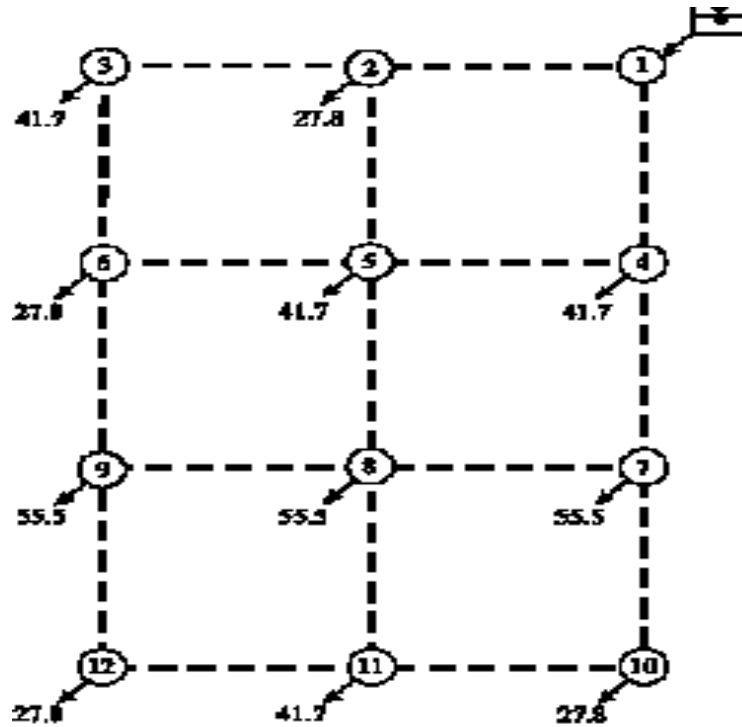


**Figure 1: Sample network (demands in litres per second)**

The use of pressure-dependent modelling in calculating the reliability of WDSs is important particularly if the severity of failures is to be accounted for properly. The techniques presented herein are yet to be applied to large water distribution systems. The emphasis so far has been on the development of theoretically rigorous, physically meaningful and computationally efficient formulations. This research is continuing on several fronts.

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