Method for water distribution systems reliability evaluation

Tina Dasic

Branislav Djordjevic

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Tina Dasic and Branislav Djordjevic
Faculty of Civil Engineering, Belgrade, Yugoslavia
E-mail: mtina@grf.bg.ac.yu

Abstract: A new methodology for water resources systems reliability evaluation is presented. The proposed methodology considers both: mechanical reliability (probability of pipe failure) and reliability of hydraulic parameters in the nodes and links (pressure, velocity). On the basis of this methodology the model NetRel was developed. This model is useful for determining reliability of systems with different configurations and complexity. Also, methodology for optimal reliability allocation, based on genetic algorithms, is proposed. That methodology, coupled with the reliability evaluation method, is an efficient tool for solving problems of optimal allocation of water distribution network reliability.

Key words: reliability, water supply systems, networks, reliability of hydraulic parameters

1. INTRODUCTION

In common engineering practice water distribution systems are designed using only heuristic criteria. Determining the optimal configuration and network parameters that can meet required flow and pressure rate are the result of hydraulic and cost-benefit analyses. The probability of system failure and other reliability statistics are very rarely included in such analyses.

Unlike other technical systems (such as car, airplane and similar systems), where reliability is an important system characteristic rigorously determined and critically analyzed, the probability of failure in water resources systems relies on examining the possibility of meeting demand under some predefined "worst case" scenarios. As a result of such practice, certain system elements are over designed, but reliability of the entire system is usually inadequate.

In the phase of planning and design of the optimal system configuration, required reliability should be included as an important parameter. Existing practice, the mutual comparison of different systems without including reliability as criteria, can lead the designer to an unreliable solution that needs further repairs or remediation.

Due to the fact that the failure of water distribution systems causes serious consequences in the social and economical environment, these characteristics have become a field of examination in the last decade.

2. NETREL - MODEL FOR RELIABILITY EVALUATION

One of the reasons that reliability has not yet become a common phase in design practice is its complexity. While the reliability of other technical systems depend only on the network configuration and the failure rate of its elements (it is defined as mechanical reliability), the water distribution system has the additional request of meeting the network hydraulic parameters. So, the demand in some node will be satisfied (the node will fulfill its task) if it is physically connected to at least one source node and if pressure is in accordance with designed levels. This second probability can be defined as the probability of meeting hydraulic parameters, or hydraulic reliability for short.

In this model (NetRel) mechanical and hydraulic reliability are coupled in overall network reliability or mechanical-hydraulic reliability. It defines the probability that the network will meet specified hydraulic parameters (specified flow and pressure in nodes and/or velocity in pipes).

Two probability measures are defined:

1) network reliability - probability that established hydraulic parameters (usually the flow and pressure rates) will be satisfied in all demand nodes (links).
2) single node reliability - probability that the defined hydraulic parameters will be satisfied in a specified demand node. Single node reliability can be of great interest when it

denotes an important consumer (hospital, school, some dangerous industry,...).

All the nodes in the network are modeled as perfectly reliable. Each link is said to have a probability r_i of functioning at any point in time, and probability $q_i=1-r_i$ of being inoperative. Links are assumed to fail independently. These assumptions may be questioned and they will certainly be the topic of future investigations, but presently they are standard assumptions defined in almost all reliability calculations.

2.1 Mechanical reliability

Mechanical reliability of the water distribution network is calculated using the main theorem of binary function decomposition. The calculation process is divided into three models (subprograms): aggregation model, system decomposition and determination sub reliability.

2.1.1 Aggregation model

The aggregation model is used to aggregate a complex system into a less complex one (tree network or purely-looped network[1]), using series and parallel aggregations.

Series aggregation is performed by replacing two links incident to the same node, with probabilities r_1 and r_2, by one link. The probability of the new link operation can be determined as $r_1 \cdot r_2$ (Figure 1a). A parallel aggregation is performed by replacing two links connected to same nodes by one link. The probability of the new link can be calculated as $1-q_1 \cdot q_2$.

The described aggregation model cannot be used to establish overall network reliability, as the reduction of any demand node effects the overall network reliability. In that case the algorithm for the calculation of the "K-node reliability", developed by Satyanarayana and Wood (Wagner et al. [1988]) is used. K-nodes are defined as nodes of interest in the network (in water distribution systems K-nodes are demand nodes). Beside K-nodes there can be others, so called simple nodes (nodes with no water demand, used only to define system configuration) in the network.

According to this method, series aggregation can be performed if either of following two conditions is satisfied: node *v* is a simple node or all three nodes are K-nodes. In the first case, new link reliability is calculated as in the previously described series aggregation method (Figure 1a). If all three nodes are K-nodes (Figure 1b) the reliability of the new link can be calculated as $r_1 \cdot r_2/(1-q_1 \cdot q_2)$, and the system correction factor (denoted by Ω) is multiplied by $(1-q_1 \cdot q_2)$. The correction factor accounts for the necessity that the middle K-node be connected to the others, even when the middle K-node seems to "vanish". After the network has been reduced the reliability of the network is found by multiplying the probability by the correction factor.

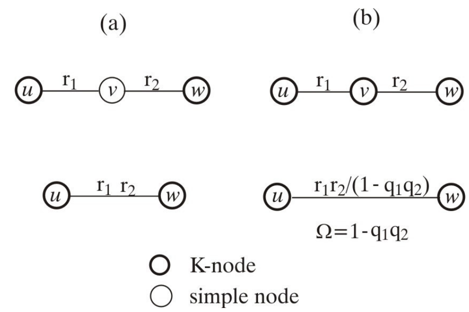

Figure 1. Series aggregations in K-nodes method

In parallel aggregations two or more links (connecting the same nodes) are replaced by new links, with greater reliability. So, there is no node reduction, and the aggregation in K-node method can be performed as previously described.

When the overall system reliability is calculated, all demand nodes are defined as K-nodes. When a single node reliability is calculated, only one node is a K-node, the node for which the reliability is calculated, while all other nodes are simple nodes (although they are defined as demand nodes).

2.1.2 System decomposition

If the result of series and parallel aggregations is a purely-looped network, the reliability of such a system can not be easily calculated. In that case the network has to be link reduced.

The method is based on main theorem of binary function decomposition. *i link decomposition* suppose the network is divided into two sub networks (Figure 2):

- $(1_i, y)$ - sub network in which the reliability of the reduced link is equal to 1 ($r_i=1$). Physically, it means that nodes connected by link *i* can be coupled into one node;
- $(0_i, y)$ - sub network with reduced link reliability equal to 0 ($r_i=0$), means that link *i* can be omitted in further reliability calculations.

[1] Purely-looped system denotes the looped system with no series or parallel connected elements.

The reliability of the new subsystem has to be multiplied by the probability that link *i* is going to operate correctly r_i and its probability of failure q_i, respectively. The overall system reliability can be calculated as:

$$R = r_i\ \psi(1_i, r) + (1 - r_i)\ \psi(0_i, r)$$

where:

$\psi(1_i, r)$ - reliability structure function of $(1_i, y)$ subsystem

$\psi(0_i, r)$ - reliability structure function of $(0_i, y)$ system

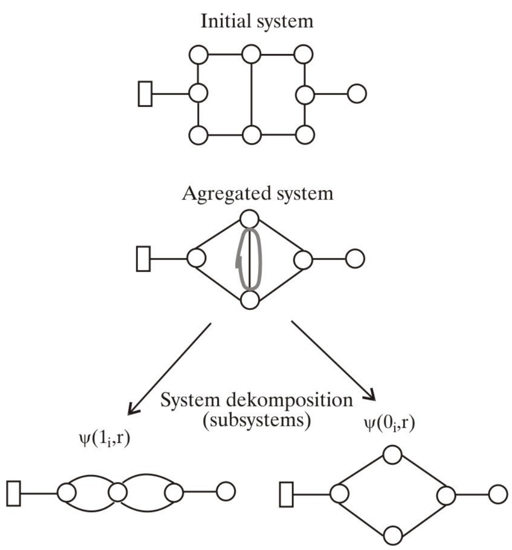

Figure 2. Principles of system aggregation and decomposition

If subsystems are purely-looped networks (i.e. the result of the aggregation model is not a tree network) then decomposition continues.

Generally, decomposition can be performed for any link in the network, but the reliability calculation will be faster if an optimal link is chosen. In this model the link for decomposition is found in two steps. Firstly, the search is performed on an aggregated network. The result of this search is the link that connects nodes in which maximal links joins. The chosen link is a path in the real (not aggregated) network. If there is at least one series connected link, it is chosen as a link for decomposition. If not, the first step is repeated. If there is more than one link with the same number of nodes repeated (in the first step), the one with the lowest link number in the path is chosen.

2.1.3 Reliability calculation

Network (or sub network) reliability can be calculated when it can be reduced to a tree of K-nodes by performing the aggregation model.

When single node reliability is calculated there is only one link connecting the source node and the demand node (specified as a K-node). Network reliability is equal to reduced link reliability. When overall network reliability is calculated the network can be aggregated to a tree network of K-nodes. Reliability can be calculated by multiplying link reliability, which is then multiplied by the reliability correction factor Ω.

Water distribution systems often rely on more than one source. That means there is more than one source node in the network. Such networks have to be modified when mechanical reliability is calculated. The problem is solved by adding an imaginary source node (Figure 3). That node is connected with real source nodes by imaginary links and has absolute reliability, its reliability is equal to 1. The new network is a network with one source node, whose reliability can be calculated as previously described.

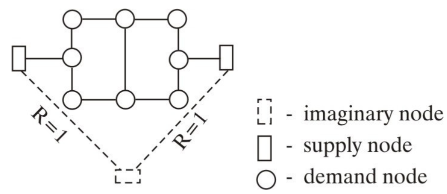

Figure 3. Imaginary node and imaginary links in network with more than one source node

2.2 Reliability of meeting hydraulic parameters

For water distribution systems connection to a source is not only necessary, but a sufficient condition to ensure that a given node is functional. That is why hydraulic calculation has to be included in determining mechanical-hydraulic reliability. Hydraulic calculation has to be performed for each subsystem for which the mechanical reliability is not equal to one (each node is connected to at least one source node).

Mechanical-hydraulic reliability can be calculated as:

$$R = \sum_{i=1}^{n} R_{meh}(S_i) \cdot R_{hyd}(S_i)$$

where n is the number of subsystems S.

If the chosen hydraulic parameters (there can be more than one parameter: pressure in nodes, velocity in links) are in specified boundary levels, the hydraulic reliability is equal to 1 (R_{hyd}=1), and mechanical-hydraulic reliability is equal to the mechanical reliability of the subsystem. If any parameter in any K-node (or link) of the system is not in desired levels, the probability of meeting the hydraulic parameters is not fulfilled, and the hydraulic reliability is equal to 0 (R_{hyd}=0).

The number of hydraulic calculations decreases if the hydraulic reliability of (0_i, y) subsystem is equal to 0. For such subsystems further decompositions will certainly form hydraulically unreliable subsystems.

3. RELIABILITY BASED OPTIMIZATION MODEL

Many authors have treated the problem of reliability allocation and optimization, but most of the attention to this issue has been given to the redundancy allocation problem. In this approach the minimum set of elements will be estimated, using genetic algorithms, in order to achieve specified system reliability with minimum cost.

The optimal design of water distribution network may be formulated as follows: for a given set of pipes and set of specified demand patterns at the nodes, find the combination of pipes which gives the minimum cost subjected to the constraint that the system reliability is better than the specified one.

The optimization model consists of several steps, usual for genetic algorithms:

1. An initial population of coded strings is generated randomly. Each string represents one network solution. The number of genes is equal to number of pipes included in optimization. Each gene is represented by one bit, which takes value 1 or 0, where 1 denotes that the pipe is included in network, and 0 denotes that the pipe is not included in the network.

2. The individuals in the current population are decoded. The result is a set of different networks. For each, network reliability is calculated using the previously described reliability evaluation model (including an additional presumption for very complex networks: only two pipes can fail at the same time). The fitness function is defined as the sum of investments in the system and a penalty function, included only for networks with reliability less than the defined one, and is calculated for each network.

3. A new population is generated using the selection operator. Individuals are selected according to their fitness, applying some of many selection procedures currently in use.

4. Crossover and mutation, genetically -inspired operators, introduce new individuals into the population.

5. Finally the replacement schemes are used to determine how the new individuals will be assimilated into the population.

Calculation procedure ends when value of fitness function is satisfied or some predefined number of iterations is achieved.

4. CASE STUDY

The proposed reliability evaluation and optimization methods are demonstrated on a hypothetical example of water distribution system. It is a system with single source node, one pumping station, 2 storage tanks, 16 demand nodes (K-nodes) and 37 links (Figure 4). This network is taken from Wagner et al, 1988, and is often used for hydraulic and reliability calculation, as it contains all the significant elements of a water distribution system.

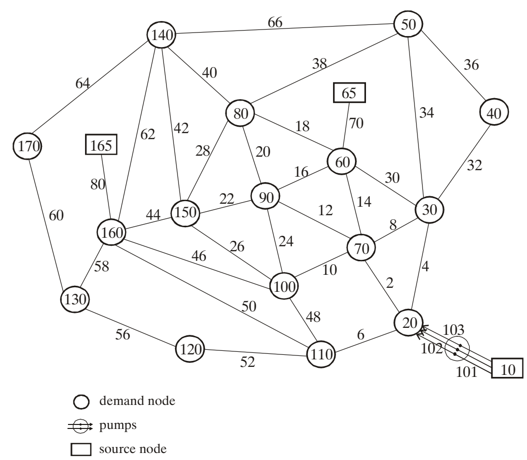

Figure 4. Case study network

The source (node 10) is at a low elevation, so water is pumped uphill from the river to downtown nodes. The pumping station is composed of three units in parallel (101, 102, 103). Pumps are assumed to fail 8 times a year, with mean repair time of 52 hours. It gives the reliability of each pump equal to 0.9543.

Demand nodes 30 - 110 are in the downtown zone, at relative elevation of 15.24 m. Nodes 120 - 170 are in a new part of town, at 36.58 m. Links are assumed to fail 0.62 times in a year on 1 km, and mean repair time is 3 days (72 hours). Specific reliability of 1 km long pipe is R_0=0.99492.

Besides the source node, there are two water tanks in the system (nodes 65 and 165). Water from these nodes can be released into the system, so they are defined as source nodes for reliability calculation. Characteristics of those nodes are same, with the same minimal and maximal water levels (Z_{min}=68.6 m, Z_{max}=76.2 m). Service head in the network is p=27.5 m, while the minimal required head in demand nodes is p=13.75 m.

Different reliability measures were calculated and analyzed for the described network. As a first step, the mechanical reliabilities for each demand node and for the overall system were calculated, using the NetRel model. Reliability of almost all nodes is close to 1. Such results were expected, as almost all nodes are connected with 4-5 links. Exceptions are nodes 40, 120 and 170, which are connected only with 2 links. That is why their reliability is slightly smaller comparing to the other nodes. The mechanical reliability of the entire network is naturally the smallest reliability, and presents the lower limit (R = 0.999611).

A result of the gathered reliability measures, and hydraulic calculations indicates that tanks are the critical elements for water supply in the system. When tanks are full, only one correctly working pump is required in the system for all nodes to be completely hydraulically satisfied (pressure in all nodes will be greater than the defined service head).

Results of mechanical-hydraulic reliability are used to calculate the average duration of water deficits in nodes and in entire the network (Figure 5). It is assumed that water tanks are full in analyzed time.

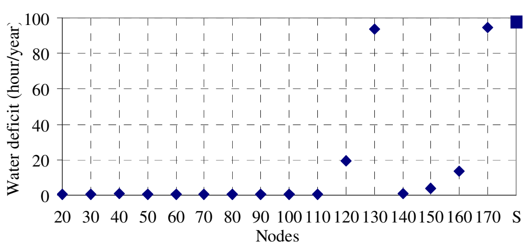

Figure 5. Nodes and network water deficits

In the case when water level in tank 65 is at a minimal level (a tank cannot be determined as a supply node and due to these circumstances cannot release water into a system), the pressure in nodes 130 and 170 will not be satisfied to service pressure level, even if all the pumps are operating. But, water deficit is not going to occur, as pressures in the aforementioned nodes will be greater than minimal network pressure (defined as 25 m).

Another scenario is when water in tank 165 is at a minimal level, tank 65 is full and all pumps are in service. Pressures in nodes of zone II would be at the minimal level (demanded water quantities would not be satisfied in those nodes). So, the critical element in the analyzed network is tank 165, on whose operation nodes of zone II depends.

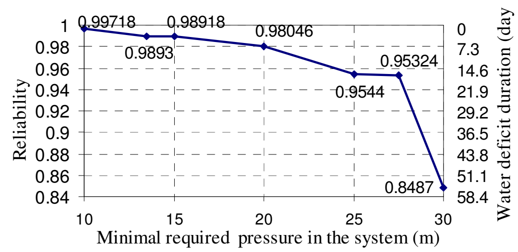

Figure 6. Network reliability and water deficit duration related to minimal required pressure in the system

Results of mechanical-hydraulic network reliability for different minimal pressures in the system are presented at Figure 6. It is assumed that tanks are full during the calculation. These reliabilities are lower than values of mechanical reliability, but they are relatively high, as a result of network connectivity and tank locations. The average duration of water deficit (expressed in days/year) is presented at Figure 6.

Node 170 of the analyzed network is the critical one, from the reliability point of view. This could be expected, as that node is in zone II and is connected to a network only through two links. In the cases when the connection to tank 165 fails, it is hydraulically not possible to supply this node from any other supply node. This is similar to node 130, with one difference - that node is connected to a network through three links. The water deficit for these two nodes is approximately 4 days/year, which is close to network reliability.

Reliability of node 120, although in zone II and connected to the network with two links (like node 170) is much higher. Its water deficit is nearly three times smaller (about one day in a year). The reason is the fact that node 120 is at the boundary between zone I and II. When the connection to tank 165 (source node) fails, node 120 can be supplied from other sources.

When tanks 65 and 165 are half full (water level is 72.9 m) network reliability is a bit smaller, with a value of 0.988362. Water deficit duration is approximately 102 hours/year. That is only a few hours in a year more than in the case when tanks are full. In both cases the system fails when connection to the tank 165 fails (link 80 fails), even if all other links in the network are operating. It is well known that the greatest reliability reductions are caused when a break in one link causes the network failure.

The optimization method is applied on presented water distribution system (for minimum allowable total head specified at each node as 27.5 m). Reliability of the system is 0.95324. The optimization problem is defined as follows:

- main objective: increase system reliability over 0.98: $R \geq R^* = 0.98$
- criteria: $f = C + C_K \rightarrow \min$, minimum of function defined as sum of additional investments in system (C) and penalty function (C_K), included only for networks with reliability les than the defined one $C_K = (R^* - R)\omega_K$
- variables: activities performed to increase system reliability. Two measures are considered: new pipes included in system (2 pipes are predicted connecting nodes 120-160 and 160-170) and pipes revitalization - increasing Hazen-Williams roughness coefficient from 70 to 125 (14 pipes)

On the base of the results of previously performed optimizations, methods based on steady state genetic algorithms were used. Analyzed methods differ in recombination type (1-point and 2-point crossover) and fitness function (according to rank and the real value of criteria function).

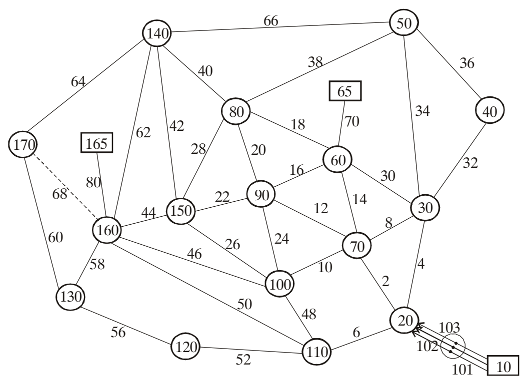

Figure 7. Optimal network solution

Obtained results indicate a fast convergence to an optimal solution: including one new pipe, pipe 68 at Figure 7. The solution, for all the examined models, is the global optimum (it was verified using enumeration method). The reliability of a new system is R = 0.98018.

5. CONCLUSIONS

The proposed model (NetRel) for calculating reliability of water distribution systems enables the determination of different reliability parameters for systems of different complexity. Mechanical and gathered mechanical-hydraulic reliability can be calculated for a single network node as well as for a whole network (probability of sufficient supply of all demand nodes in network). It can also be easily used for determining the reliability of other technical systems.

Furthermore, the reliability evaluation model has been incorporated in an optimization model (based on evolutionary programming). This model can be used for water distribution system optimization (for planning new systems or the reconstruction of an existing system). The optimization objective is to increase system reliability, with minimum investment in the system. The model was analyzed for different networks (different optimization problems). In a number of cases the results were very close or equal to the global optimums of the analyzed optimization problem.

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