

WATER DISTRIBUTION SYSTEM RELIABILITY BASED ON MINIMUM CUT - SET APPROACH AND THE HYDRAULIC RELIABILITY

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ABSTRACT

Reliability analysis of water distribution systems is a complex task, as it requires both definition and calculation of several reliability measures. In this paper, a methodology for evaluating water distribution system reliability is developed and demonstrated on a simple water distribution network based on the minimum cut-set method. The definition of the minimum cut-set can arise from either from the mechanical reliability or from the concept of hydraulic reliability. In case of mechanical reliability, a new method in order to determine the minimum cut-sets, based on graph theory, is developed. This method is based on the counting of paths between vertices. Furthermore, the general concept of reliability is proposed to include apart from the mechanical reliability, more generally, the pressure availability at nodes as a main hydraulic property. Based on the pressure availability the sense of hydraulic availability can be expressed as a fuzzy set, while the combination of the water unavailability of the nodes can be achieved by using aggregators of the fuzzy intersection. Finally an overall reliability index is proposed based on both the hydraulic and mechanical reliability. An illustrative example is developed to indicate the methodology.

1 INTRODUCTION

Water distribution system plays a vital role in preserving and providing a desirable life quality to the public, of which the reliability of supply is a major component. Reliability analysis of a Water Distribution System (WDS) is concerned with its ability to deliver water to individual consumers in the required quantity and quality and under a satisfactory pressure (Al-Zahrani and Syed, 2005).

Reliability of water distribution system is defined by Kaufmann et al. (1977) as the probability that the system will perform its specified tasks under specified conditions and during a specified time. Many researchers (Goulter (1995), Cullinane et al. (1995)) defined reliability of water distribution system as the ability of the system to meet the demands that are placed on it. The demands are specified in terms of the flow to be supplied and the range of pressure at which these flow rates must be provided.

In conclusion it is noticeable that the reliability is an ill-constructed sense with no universally accepted definition exists in the literature (Shinstine et al., 2002). In any

case the reliability includes the vulnerability of the hydraulic supply networks under specified conditions.

The minimum cut-set method is usually used in order to investigate the topology of a water distribution network and the detection of its critical elements whose failure will affect the network operation. The minimum cut-set is a set of system components which, when failed, causes failure of the system but if just one component of the set has not failed no failure of the system occurs. Following the cut-set method an estimation of the *mechanical reliability* of a hydraulic network can be achieved.

In this paper a methodology based on the adjacent matrix is developed in order to determine computationally the minimum cut-sets.

2 PIPE FAILURE PROBABILITIES

Goulter and Coals (1986) and Su et al. (1987) used similar methods to determine the probability of failure of individual pipes based on the Poisson probability distribution as follows:

$$P_i = 1 - e^{-\beta_i}, \text{ where } \beta_i = r_i L_i \quad (1)$$

β_i is the expected number of failures per year for pipe i and r_i is the expected number of pipes failures per year per unit length of pipe, i and L_i is the length of pipe i .

3 THE PROPOSED METHOD OF ADJACENT MATRIX

3.1 Basic principles of Graph Theory

A simple graph $G = (V, E)$ consists of V , a nonempty set of vertices, and E , a set of unordered pairs of distinct elements of V called edges.

It should be noticed that in case of hydraulic networks the vertices is called *nodes* while the edges is called *pipes*. To simplify the various application of graph theory, it is widely proposed that the graphs can be presented using matrixes.

Let a Graph with arbitrary vertices $v_1, v_2, \dots, v_n$. The adjacency matrix A of G , with respect to this listing of the vertices, is the $n \times n$ zero –one matrix with elements equal to 1 as its $(i, j)^{th}$ entry when v_i and v_j are adjacent and 0 as its $(i, j)^{th}$ entry when they are not adjacent. In other words if its adjacency matrix is $\mathbf{A} = [a_{ij}]$, then (e.g. Rosen, 2003 Spiliotis and Siettos, 2011):

$$a_{ij} = \begin{cases} 1 & \text{if } \{v_i, v_j\} \text{ is an edge of } G \\ 0 & \end{cases} \quad (3)$$

The adjacent matrix of a simple graph is symmetric, that is,

$$a_{ij} = a_{ji} \quad (4)$$

since both of these entries are 1 when v_i and v_j are adjacent and 0 otherwise. Moreover in our case we suppose that the self -loops have not physical meaning, that is

$$a_{ii} = 0 \quad (5)$$

For example concerning the pseudograph of Fig.1(b), the adjacent following matrix using the ordering of vertices 1, 2, 3, 4 has the form:

$$A = \begin{bmatrix} 0 & 1 & 0 & 2 \\ 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 \\ 2 & 1 & 1 & 0 \end{bmatrix}$$

The elements with no binary value and the bias element with non zero values is out of physical meaning in case of water supply networks. Obviously the graph presented at Fig.1(a) can represent a looped WDS which analyzed in the example.

From the example presented above, it is obvious, that in case of pseudographs, the adjacency matrix is not a binary matrix but this fact, has not physical meaning in our problem.

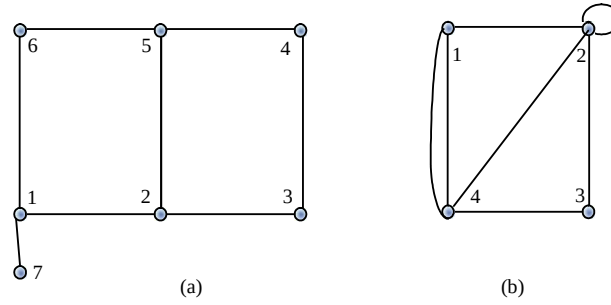


Figure 1. (a) A graph which may describe an looped WDS and (b) a pseudograph which can not describe properly an looped WDS.

Another interesting sense which is used, is the path. The path is a sequence of edges that begins at a vertex of a graph and travels along edges of the graph, always connecting pairs of adjacent vertices.

Let n be a nonnegative integer and G an undirected graph. A *path* of length n from u to v in G is a sequence of n edges $e_1, e_2, \dots, e_n$ of G such that:

$$f(e_1) = \{x_0, x_1\}, f(e_2) = \{x_1, x_2\}, \dots, f(e_n) = \{x_{n-1}, x_n\}, \text{ where } x_0 = u \text{ and } x_n = v \quad (6)$$

When the graph is *simple*, we denote this path by its vertex sequence $x_0, x_1, \dots, x_n$ (since listing these vertices *uniquely* determines the path). The path is a circuit if it begins and ends at the same vertex, that is, if $u = v$, and has length greater than zero. A path or circuit is simple if it does not contain the same edge more than once.

Obviously in case of the network connectivity the repetition of a node (vertex) in a path has no physical meaning and therefore, we focus on the examination of the simple path.

3.2 The proposed algorithm to determine the minimum cut-set

By comparing the strict mathematical formulation with the case of looped WDS the first think is the correspondence of the edges with the pipes and the nodes of the network with the vertices. In looped WDS it is not possible to guarantee the direct of the

flow, therefore the use of simple graph theory is further required.

Another interesting point of view is that we focus on the distinction between the *demand nodes* and the *source nodes*. Obviously this does not hold in this form in the mathematical formulation of the simple graphs.

Moreover in this work only the sense of simple path is used since the direction of flow is not known in a looped WDS while usually only one branch connects two, nodes. A critical theorem which is used in this paper is the theorem of counting paths between vertices.

Theorem 1: Let G be a graph with adjacent matrix $\mathbf{A}$ with respect to the ordering $v_1, v_2, \dots, v_n$. The number of different paths of length r from v_i to v_j , where r is a positive integer, equals the $(i, j)^{th}$ entry of $\mathbf{A}^r$ (Rosen, 2003).

Furthermore in our case of simple path, the number of paths that connective two nodes is not infinitive and moreover it can be determined following the next theorem (Theorem 2):

Theorem 2: Let the number of vertices (nodes) is equal to NN . Then the maximum number of edges (pipes) in a simple path, which connectives two arbitrary vertices (nodes) is equal to $NN-1$ (Spyrou, 1997).

Therefore the maximum pipes which may be contained in a simple path between a water source node and a water demand node is equal to $NN-1$.

According to strict mathematical formulation obviously there is the opportunity to exist (no simple) paths with more than $NN-1$ edges (pipes) between two vertices. This fact in looped WDS is without physical meaning.

Therefore to check the mechanical connectivity between two nodes the following reasoning is ensured:

It is sufficient to exist at least a simple path between the demand nodes and at least one source - node.

The maximum number of pipes in a simple path between the demand node and the source node is $NN-1$.

If there in not any path with at most $NN-1$ number of pipes it is obvious that there is not connectivity for this node.

Finally to check if there is any connectivity between a source node i and a demand node j it is sufficient to check if the element $\mathbf{B}(i, j)$ of the following matrix $\mathbf{B}$ is different from zero:

$$\mathbf{B} = \mathbf{A}^1 + \mathbf{A}^2 + \dots + \mathbf{A}^{NN-1} \quad (7)$$

in which NN is the total number of nodes and $\mathbf{A}$ is the adjacent matrix.

Obviously if $b_{ij} \neq 0$ then, there is at least one path with a number of edges equal or smaller than $NN-1$ while if $b_{ij} = 0$ then, there in not any connectivity between i and j .

Instead of the mathematical formulation of graph theory, in looped WDS it is sufficient for every row to exist at least a non- zero element at the corresponding columns of water source nodes, while in the mathematical formulation of graph theory it is required, that every element at every row has no zero value.

Finally in order to check the hydraulic connectivity the following algorithm was established:

Step (a) We determine the adjacent matrix of the looped WDS.

Step (b) Let ns the number of the water sources. We mark the corresponding columns of water source nodes.

Step (c) We null the corresponding elements of the adjacent matrix for each scenario of pipes break.

Step (d) We calculate the matrix:

$$\mathbf{B} = \mathbf{A} + \mathbf{A}^2 + \dots + \mathbf{A}^{NN-1}$$

Step (e) If, for any row of $\mathbf{B}$, there is at least an element with non-zero value at the corresponding columns of water sources, except the b_{ii} element, then there is a mechanical connectivity between the demand nodes and the water sources, otherwise there is not.

Consequently to check if one or more pipe is a minimum cut-set it is enough to change the corresponding elements of the adjacent matrix and after that to check if the connectivity between the demand nodes and at least, one water source node remains. Obviously a minimum cut-set element can not belong to other larger minimum cut-set element.

4 RELIABILITY BASED ON MINIMUM CUT-SET

According to Shinstine et al. (2002), for n components (pipes) in the i th minimum cut - set of a water distribution system, the failure probability of the i th minimum cut-set (MC_i) is:

$$P(MC_i) = \prod_{j=1}^{ncp} p_j \cdots p_{ncp} \quad (8)$$

where ncp the number of the pipe broken in this minimum cut-set or in other words the number of the element of the corresponding minimum cut-set.

Using the step function for hydraulic availability and assuming that the occurrence of the failure of the components within a minimum cut-set is statistically independent, for a water distribution network with e.g. four minimum cut-sets (MC_i) with for a with the system reliability, R_s , the failure probability of the system P_s is then defined as:

$$P_s = P(MC_1 \cap MC_2 \cap MC_3 \cap MC_4) \quad (9)$$

By applying the principle of inclusion and exclusion (Ross, 1985) Eq. 8 can be approximately reduced to:

$$P_s = P(MC_1) + P(MC_2) + P(MC_3) + P(MC_4) \quad (10)$$

In general form the probability of failure can be determined as:

$$P_s = \sum_{i=1}^M P(MC_i) \quad (11)$$

in which M is the number of minimum cut-set in case that a significant number of minimum cut-set exist (Yannopoulos and Vohaitis, 2003 and Yannopoulos et al., 1997). The above approximation is applied by investigating the failure of at most three pipes since from Eq.8 the probability of more pipe break has no practical meaning.

Finally the system reliability, R_s , is expressed as follows:

$$R_s = 1 - P_s = 1 - \sum_{i=1}^n P(MC_i) \quad (12)$$

As mentioned before the calculation of the minimum cut-sets, presented in the previous section, is based on the mechanical reliability of the nodes. The above reliability index can be interpreted as a mean disconnectivity of the looped WDS. Although the probability of break depends on the characteristics of the network (Eqs.1 and 2) it can be said that the mechanical reliability is mainly depend on the topology of the network.

Unfortunately in case of pipes break, it is possible to occur pressure unavailability at nodes, even if, the connectivity of the nodes with at least one water source node remains for the looped WDS. Consequently a more comprehensive definition of the minimum cut-sets and the corresponding reliability should be used.

5 RELIABILITY BASED ON HYDRAULIC AVAILABILITY

Hydraulic availability, as it relates to water distribution system design, can be defined as the ability of the system to provide service with an acceptable level of interruption in spite of abnormal conditions (Cullinane et al., 1992). The evaluation of hydraulic availability relates directly to the basic function of the water distribution system, i.e., delivery of the specified quantity of water to a specific location at the required time under the desired pressure (Shinstine et al., 2002). Although apart from the pressure constraint, other hydraulic constraints must be examined (e.g. the velocity constraint) we focus on the pressure constraints.

At first the hydraulic availability is defined for each node based on the pressure constraint. It is rather more reasonable to use the fuzzy definition which incorporates the sense of granularity instead of the crisp definitions proposed earlier by Goulter and Coals (1986) and Su et al (1987). In general, the methodology of fuzzy sets comprises a mapping from a general set X to the closed interval $[0,1]$ which is described by its membership function, μ (e.g. Papadopoulos and Sirpi, 1999). The membership function of the hydraulic availability at each node, μ_{pk} , is presented at Fig. 2. Obviously the membership function of the hydraulic availability depends on the number of floors at the network serviced community.

By using the negation of the crisp logic, the hydraulic unavailability $UNAVAIL_k$ at a water consumption node can be defined as follows:

$$UNAVAIL_k(h_{pk}) = 1 - \mu_{pk}(h_{pk}) \quad (13)$$

Having all the individual membership functions of all major elements, the problem is to determine a global evaluation through a proper fuzzy operator with respect to all nodes. Most technical and environmental standards are based on the non-compensatory combination rule (Tsakiris et al., 2009). Among various fuzzy aggregators of fuzzy intersection (Klir and Yuan, 1995) the *algebraic product* is widely used because it takes over the degree of satisfaction of all membership functions. Following the algebraic product the overall hydraulic unavailability can be expressed as follows:

$$UNAVAIL = \prod_{k=1}^n (1 - \mu_{pk}(h_{pk})) \quad (14)$$

in which n is the number of water consumption nodes and i denotes the case of pipes breakage.

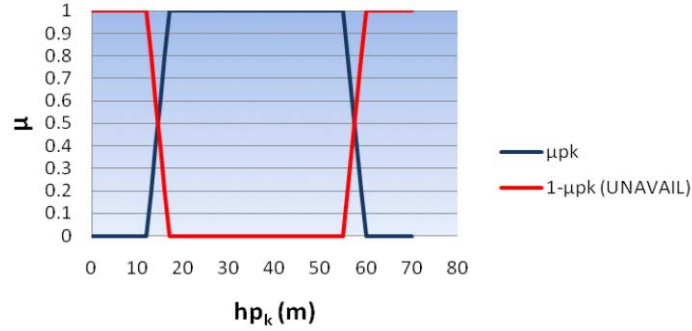


Figure 2. Membership function, μ_{pk} , of hydraulic availability at node k and the membership function of its complement, UNAVAIL.

Apart from the algebraic product other fuzzy aggregators can be used such as the classical *min-intersection*, which is the intersection of the crisp logic. By using the min-intersection instead of the algebraic product the overall hydraulic unavailability can be expressed as follows:

$$UNAVAIL' = \min_{k=1, \dots, n} (1 - \mu_{pk}(h_{pk})) \quad (15)$$

It fact it is widely proposed the extension of the minimum cut-sets by using the hydraulic unavailability (e.g. Shinstine et al., 2002) with the aid of mathematical functions without a logical interpretation foundation. It is also noticeable that according to the foundation of fuzzy logic the fuzzy intersection is defined axiomatically. All functions which satisfy the axiomatic skeleton of fuzzy intersection are fuzzy intersections (e.g. Klir and Yuan, 1995). Furthermore from the axiomatic definition of fuzzy intersection it is concluded that in case that a node has completely zero hydraulic unavailability, that is $UNAVAIL_k(h_{pk}) = 0$ for a node k , then the total hydraulic unavailability is also equal to zero, even if, the other nodes have significantly no zero values.

By selecting the algebraic product to combine the hydraulic unavailability at each node the overall hydraulic unavailability is determined as follows:

$$TUNAVAIL_i = \begin{cases} \prod_{k=1}^n (1 - \mu_{pk}(h_{pk})) & \text{if } \prod_{k=1}^n (1 - \mu_{pk}(h_{pk})) > \bar{p} \\ 0 & \text{if } \prod_{k=1}^n (1 - \mu_{pk}(h_{pk})) \leq \bar{p} \\ 1 & \text{if arises from mech. unavail.} \end{cases} \quad (16)$$

While by selecting the min intersection to combine the hydraulic unavailability at each node the overall hydraulic unavailability is alternatively determined as follows:

$$TUNAVAIL_i' = \begin{cases} \min_{k=1,\dots,n} (1 - \mu_{pk}(h_{pk})) & \text{if } \min_{k=1,\dots,n} (1 - \mu_{pk}(h_{pk})) > \bar{p} \\ 0 & \text{if } \min_{k=1,\dots,n} (1 - \mu_{pk}(h_{pk})) \leq \bar{p} \\ 1 & \text{if arises from mech. unavail.} \end{cases} \quad (17)$$

From Eq. 16 or alternatively from Eq. 17 it is obvious that the sense of minimum cut-sets is expanded with the use of hydraulic unavailability. Obviously if a pipe (or a set of pipes) destroys the connectivity of at least one node with the water source node then the index of total unavailability, for this scenario, takes one value. Therefore, according to the proposed method for each scenario of pipes break firstly the connectivity between demand nodes and the water supply sources is checked (see section 3.2) and secondly (if the connectivity remains) we examine the pressure availability at each node and the corresponding overall index by solving the looped network for this scenario. Finally the overall system reliability, R_s , is expressed as as the product of pipe reliability and hydraulic unavailability as follows:

$$R_s = 1 - P_s = 1 - \sum_{i=1}^n TUNAVAIL_i \cdot P(MC_i) \quad (18)$$

6 APPLICATION AND DISCUSSION

Let the simple looped WDS presented at Fig.3. The node (7) is a source node (tank) while the other nodes are demand nodes.

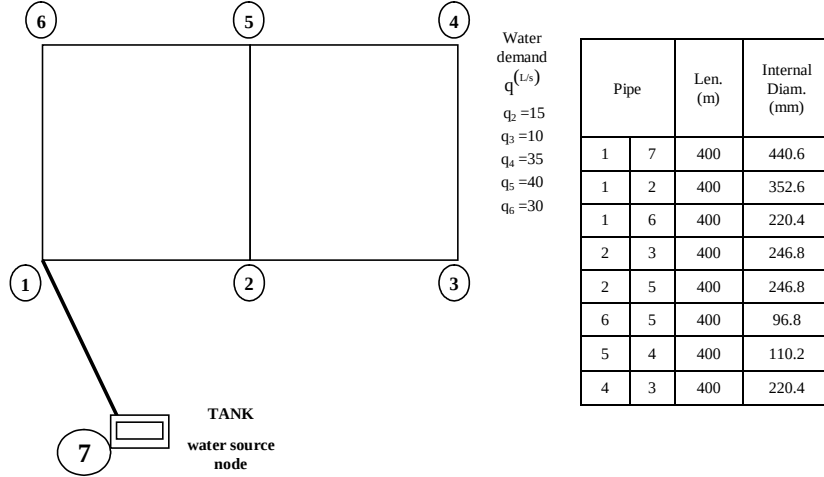


Figure 3. The looped pipe network under study

The presented network has the following adjacent matrix using the ordering of vertices (nodes) 1, 2, 3, 4, 5, 6, 7:

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Further aiming at presenting the methodology we examine if the break of both the pipes 2-3 and 3-4 creates a minimum cut-set. In this case the adjacent matrix has the following form:

$$\mathbf{A}' = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 0 & \mathbf{0} & 0 & 1 & 0 & 0 \\ 0 & \mathbf{0} & 0 & \mathbf{0} & 0 & 0 & 0 \\ 0 & 0 & \mathbf{0} & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The 6th power of the adjacent contain (at least) the element $\mathbf{B}(3, 7)$ with zero value that is, the node 3 has not connectivity with the water source (node 7). It is noticeable that the other nodes remain the connectivity with the water source node since the other elements of column 7, from 1 to 6, have no zero values:

$$\mathbf{B} = \mathbf{A}'^1 + \mathbf{A}'^2 + \mathbf{A}'^3 + \mathbf{A}'^4 + \mathbf{A}'^5 + \mathbf{A}'^6 = \begin{bmatrix} 79 & 31 & 0 & 14 & 76 & 31 & \mathbf{17} \\ 31 & 62 & 0 & 31 & 31 & 62 & \mathbf{31} \\ 0 & 0 & 0 & 0 & 0 & 0 & \mathbf{0} \\ 14 & 31 & 0 & 17 & 17 & 31 & \mathbf{14} \\ 76 & 31 & 0 & 17 & 79 & 31 & \mathbf{14} \\ 31 & 62 & 0 & 31 & 31 & 62 & \mathbf{31} \\ 17 & 31 & 0 & 14 & 14 & 31 & \mathbf{17} \end{bmatrix}$$

On the other hand if the pipes (1-6) and (2-5) are broken then the 6th power of the corresponding adjacent contain no element with zero value that is, the pipes (1-6) and (2-5) are not create a minimum cut-set.

Finally the minimum cut - sets based on exclusively the mechanical reliability (Eq. 12) are presented at Table 1 (2nd column). The calculation is based on the proposed method at section 3.2. A programme in MATLAB R2008, is developed by the authors for this purpose. At first, the programme creates all the candidate minimum cut-sets for each combination of pipes break. Due to the fact that the probability of failure is about $\bar{p} = 0.04$, the scenario of more than 3 pipe break has no practical meaning. The method presented by Spiliotis and Tsakiris (2011) is chosen to solve the network for various scenarios for computational facility.

Apart from the calculation of the minimum cut-sets based on the mechanical

reliability the calculation based on the overall hydraulic reliability is also applied in this application (third column at Table 1). In this case, the minimum cut-set with one pipe break combination contains more pipes compared with the previous minimum cut-set. Although this fact causes no minimum cut-sets at the second and third combination of pipes break for this application, the total reliability (Eq. 18) takes smaller value compared with this calculated based on Eq. 12 since the cut-set of the first combination (one pipe break) of the third column is significantly more than the second column. The flowchart of the applied algorithm based on hydraulic unavailability is presented in the Appendix.

Table 1. Minimum cut -sets

Number of broken pipes	Without hydraulic unavailability	Including hydraulic unavailability based on algebraic product to combine the nodal unavailability
1	(7-1)	(7-1) , (1-2), (2-3), (3-4), (6-1), (2-5)
2	(1-2)-(5-6), (1-2)-(6-1), (2-3)-(3-4), (2-3)-(4-5), (3-4)-(4-5), (5-6)-(6-1)	-
3	(1-2)-(2-3)-(2-5), (1-2)-(2-5)-(3-4), (1-2)-(2-5)-(4-5), (2-3)-(2-5)-(5-6), (2-3)-(2-5)-(6-1), (2-5)-(3-4)-(5-6), (2-5)-(3-4)-(6-1), (2-5)-(4-5)-(5-6), (2-5)-(4-5)-(6-1)	-
Reliability index	1-0.00502	1-0.24

It is noticeable that the hydraulic availability requires not only the topology and the probability of pipe break but also all the parameters which are required to solve the looped network, while the mechanical reliability index is mainly requires the topology of the network.

Another point of view is that the choice of the fuzzy intersection does not influence significantly the final reliability index.

The examination of the tank reliability, as a individual element of the network, is a topic for further examination. Another point of further investigation is the integrated presentation of hydraulic unavailability and the aggregation of the nodal hydraulic unavailability by several fuzzy aggregators, supposing various weight of nodes based on the corresponding population at nodes.

7 CONCLUDING REMARKS

Reliability analysis of a water distribution system is rather an ill-constructed sense, and it may be defined as the ability of the looped WDS to operate satisfactory under specified conditions. Lying in this definition, a widely used method is the minimum cut-set and the corresponding reliability.

The determination of the minimum cut-sets can be based either on the mechanical or the hydraulic availability.

In case that the determination of the minimum cut-set is based on the mechanical reliability then the graph theory can be used in order to simplify the calculation of minimum cut-set. In fact in this case the reliability expresses the mean nodal disconnectivity of the looped WDS. However, some modifications are required since

the distinction between the demand and the water source nodes do not hold in the classical disconnectivity theory. The determination of the minimum cut-set can be achieved by a proposed algorithm which is based on the adjacent matrix and other principles of graph theory.

In the second case the sense of hydraulic reliability, apart from the nodal disconnectivity, includes the more general sense of hydraulic unavailability. In this work the use of fuzzy operators is proposed in order to achieve a rational foundation of the hydraulic unavailability and the corresponding reliability indexes mainly based on the fuzzy intersection.

The first approach of the mechanical reliability can be used to check the topology of the network and it should be proved a critical tool at a first design stage, while the second approach of hydraulic availability incorporates all the parameters of the network and therefore it is strongly proposed for a final evaluation of the looped WDS.

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APPENDIX

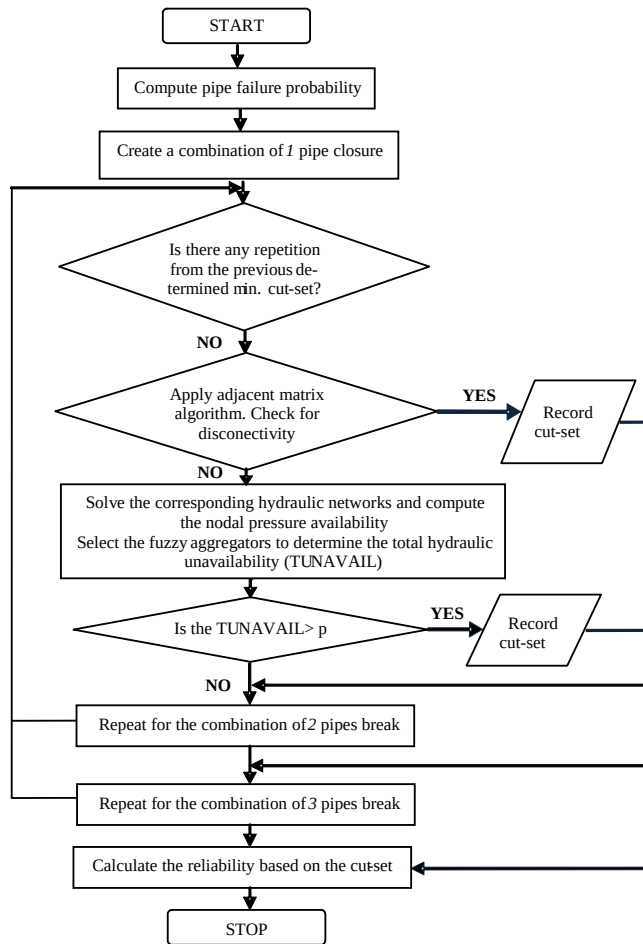


Figure A. Minimum cut set reliability flowchart based on the hydraulic unavailability