

1 **Impact of location of isolation valves on resilience of water distribution**
2 **systems**

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3 **Abstract**

4 The isolation valves are crucial components of water distribution systems (WDS) that
5 are used to shut down a segment of the network to repair or replace failed pipes. In this
6 paper an algorithm to find adjacent valves to isolate a failed pipe was proposed and the
7 global resilience analysis method was implemented to find out the critical segments
8 based on the isolation valves. The method was applied to Net3 network with three
9 different isolation valve configurations.

10 The location of isolation valves changed the resilience of the WDS considerably. The
11 critical pipes and segments were also varied with different valve configuration. More
12 than 60 % of the most critical pipes are different between N valves and N-1 valves
13 configurations. The resilience of Limited valves configuration (with 52 valves) was
14 22% and 15 % less than the resilience of N valves and N-1 valves configurations with
15 228 and 105 valves respectively. Furthermore, with adding valves to the critical
16 segments, the resilience can be enhanced noticeably.

17 Keywords: GRA; critical segments, supply shortage, reliability

18 **Subject classification codes: include these here if the journal requires them**

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25 **1-Introduction**

26 Water distribution systems (WDS) are the crucial component of urban infrastructure that play
27 a critical role in delivering sufficient water to users with acceptable pressure, volume and
28 quality. Occurrence of a pipe failure may interrupt service, undermine system performance

1 and ultimately lead to consumer dissatisfaction (Tabesh et al. 2009). More serious condition
2 occurs when several pipes in the system fail simultaneously (Gheisi and Naser 2014).

3 Nowadays, the threat of accidental or man-made disruptions motivates water utilities
4 to plan risk mitigation works and to improve the preparedness for extreme events (Berardi et
5 al. 2014). Pipe breaks increase with aging infrastructure, natural disasters such as earthquakes
6 and man-made disruptions (Klise, Murray, and Haxton 2018). Three criteria; reliability,
7 resiliency and vulnerability have been used to assess the performance of the water
8 distribution system (Hashimoto, Stedinger, and Loucks 1982). The resilience capacities are
9 absorptive, adaptive and restorative that a system needs to be able to respond to perceived or
10 real shocks (Francis and Bekera 2014). Butler et al. (2017) defined the resilience in WDSs as
11 “the degree to which the system minimizes level of service failure magnitude over its design
12 life when subject to exceptional conditions”. Failure modes in WDSs can be broadly
13 categorized into structural failure and functional failure (Mugume et al. 2015). Response to
14 pipe failure can indicate system resilience to loss of structural connectivity (Butler et al.
15 2014).

16 Todini (2000) proposed a technique based upon the definition of resilience index that
17 emulate both reducing the cost and preserving a capability of the system to overcome failures
18 while still satisfying demand and pressure at each node. Baños et al. (2011) analyzed the
19 quality of several resilience indices, i.e., resilience index, RI (Todini, 2000), network
20 resilience index, NRI (Prasad and Park (2004), modified resilience index, MRI (Jayaram and
21 Srinivasan (2008) for WDSs. They showed that these resilience indices did not consider the
22 location of over-demand occurrence. Monsef et al. (2019) evaluated six well-known
23 reliability assessment indicators (RI, NRI, MRI, minimum surplus head (MSH), total surplus
24 head (TSH), entropy reliability indicator (ERI)) in five WDSs under a large number of

1 abnormal operating conditions. They showed that some WDS structures, in spite of having
2 higher reliability indicator values, are unable to adequately tolerate abnormal conditions.

3 Berardi et al. (2014) proposed an evolutionary strategy to assess WDS vulnerability
4 with scenarios that a minimum fraction of failed pipes caused maximum shortage of water
5 supply. For evaluating resilience, it is important to include high-stress scenarios that happen
6 occasionally with low probability (Johansson et al., 2013). Identification of performance
7 strains resulting from any stress magnitude requires no knowledge of the causal threats. This
8 approach has been adopted in global vulnerability analysis (GVA) of power grids and for
9 global resilience analysis of water distribution systems (Johansson, 2007; Hokstad et al.,
10 2012; Johansson et al., 2013; Mugume et al. 2015; Diao et al., 2016). Diao et al. (2016)
11 proposed the Global Resilience Analysis (GRA) as a methodology that focusses on the
12 response to system failure modes. GRA provides an overview of a water system's resilience
13 to various failure modes. For each failure mode, it identifies the range of corresponding
14 failure impacts and reveals extreme scenarios.

15 In most reliability researches, pipe breaks were modeled by removing individual pipes
16 from a network model without considering the location of isolation valves (Fujiwara and Li
17 1998; Dandy and Engelhardt 2001). In the pipe failure mode of GRA, the stress is also
18 modeled by isolating pipes shortly after breakage so that the 'failed pipes' have been modeled
19 by changing the status of them to completely closed for a duration of 3 hours in peak demand
20 period (Diao et al. 2016). This requires existence of two valves on both ends of each pipe so
21 that each pipe can be repaired or replaced individually. In practice, a subsystem isolation is
22 required to repair or to rehabilitate a failed pipe and usually done by closing the adjacent
23 valves. In the other words, depending to availability of isolation valves more than one pipe
24 may need to be closed to repair or replace a failed pipe. Isolation valves play a key role in
25 management of WDSs for isolation of subsystems and flow or pressure control (Jun 2005;

1 Walski, Weiler, and Culver 2008). Therefore, to isolate a portion of a network, isolation
2 valves must be considered in the network (Walski 1987; Jose and Sumam 2016; Walski
3 2002).

4 Walski (1993) showed the importance of adequate valving to enhance the reliability
5 of WDSs. Walski (2002) proposed a method for fire flow simulation by closing individual
6 pipes versus segments. The results showed that the valves should be considered in
7 connections to main pipes so that during a failure at a smaller line, the main pipes not to be
8 part of a segment. Many studies have focused on identification of network segments and
9 unintended isolation of the network by valve closure (Blokker et al. 2011; Giustolisi,
10 Kapelan, and Savic 2008; Jun and Loganathan 2007). Kao and Li (2007) proposed a segment-
11 based model for pipeline replacement to improve water supply reliability. Several researchers
12 including Giustolisi and Savic (2010), Creaco et al. (2010) and Pecci et.al.(2017) presented a
13 method for optimal placement of valves in WDSs to increase network reliability.

14 The design guideline proposed by Mays (2000) suggested placing valves at both ends
15 of each pipe. Ysusi (1999) also recommended the valves to be placed on each pipe at every
16 junction to maximize the network performance. However, the number of valves in real
17 networks is always less than this guideline due to budget constraints. There are also other
18 general guidelines for valve placement in a WDSs (Lakes and Board 1992; Rosenthal,
19 Mesman, and De Koning 2002). Based on these guidelines, the spacing between two valves
20 should be less than 500 ft in business area, and less than 800 ft otherwise. At least two valves
21 at a T-junction and three at a cross-section have been recommended.

22 The most of above mentioned researchers adopted the "N Valves" and "N-1 Valves"
23 rule for modeling the impacts of isolation valves failure. The "N Valves" configuration is a
24 valve layout where the number of valves is equal to the linked pipes at a junction, and "N-1
25 Valves" is a style of valving one less than the linked pipes (Jun and Loganathan 2007; Alvisi,

1 Creaco, and Franchini 2011; Giustolisi and Savic 2010; Giustolisi, Berardi, and Laucelli
2 2014; Jose and Sumam 2016; Liu et al. 2017; Walski, Weiler, and Culver 2008). Giustolisi
3 (2018) developed a WDS reliability assessment indicator based on the supplied demand and a
4 modularity index for the isolation valve system (IVS) performance assessment. The network
5 performance was evaluated by risk of disconnection, i.e. the probability of segment failure
6 per the required customer demand over time.

7 Meng et al. (2018) proposed a framework based on graph theory for the optimized
8 placement of new valves based on resilience assessment. Resilience was measured by failure
9 severity in a segment (measured in L) as the production of the longest replacement time
10 (hours) of pipes in a segment and the unsatisfied water demand (L/h) due to valve closures
11 for repair. Unsatisfied water demand was assessed and the reduction in water delivery due to
12 low pressure was not considered. They studied single valve addition and the location of the
13 added valve was optimized.

14 In this paper, the global resilience is assessed by considering different valve
15 configurations including "N Valves", "N-1Valves" and "Limited Valves" in Net3 network
16 and the results are compared. An efficient algorithm to identify the isolation segment based
17 on adjacent valves to each pipe is also proposed. The critical pipes and segments in each
18 valve configuration are specified based on GRA method.

19 **2- Method and material**

20 After pipe breaks, some damages are minor and therefore can be repaired, while other
21 damages are more serious and require a replacement of pipe sections. During reparation,
22 there may be no need to isolate the pipe, although the pipe will continue leaking until the
23 repair is finished, However, during a replacement, the isolation is necessary and fixing the
24 broken pipe will not start until it is isolated using the necessary valves (Paez, Fillion, and

1 Hulley 2018). In N valves configuration, each pipe can be isolated individually. While in the
2 other valve configurations, a method is required to find the adjacent isolation valves to isolate
3 a segment of the network to replace the failed pipe.

4 ***2-1-Identifying isolation segments***

5 To model a pipe failure, it is required to close the corresponding isolation valves that separate
6 the segment including that pipe. Adding an isolation valve on each pipe in EPANET2, the
7 pipe is divided into three sections. Hence, an isolation valve acts as a short connector. To find
8 the isolation valves of each pipe, based on the start and end nodes of pipes and valves, all
9 nodes are searched.

10 The procedure to identify the adjacent isolation valves of each pipe after loading the
11 network hydraulic model with existing valves is as follows (Figure):

12 Step 1. Load basic WDS information.

13 Step 2. Separate pipe list and valve list with start and end nodes.

14 Step 3. Consider a pipe, the start and end nodes of that pipe are compared with all
15 valves start and end nodes. Then three different situations may happen:

16 a- The start and end nodes of a pipe are the same as the start or end nodes of two
17 different valves, which means that there exist two valves at both ends of that pipe.

18 b- One of the pipe start or end nodes is the same as a valve start or end nodes which
19 means that there is a valve on one end of the pipe.

20 c- None of the pipe ends are the same as valves ends, which shows no valve in this
21 pipe.

22 Step 4. In case (a) there are two valves at ends of the pipe, thus the pipe failures is
23 modelled with simply closing the identified valves. In cases b and c, one or two pipe

1 ends are connected to adjacent pipes. For the connected pipes step 3 is repeated up to
2 reaching an existing valve. Then the pipe and valve lists are updated for that segment.
3 Step 5. Repeat the process to find all isolation segments.

4 As an example when pipe 2 (P2 in Figure) is failed, three isolation valves should be
5 closed (valves 1-3) to isolate this pipe. Therefore, four other pipes are also shut off (i.e., e1,
6 e2, e3 and P3). When there are valves at both ends of each pipe (such as P4 in Fig. 2), the
7 status of P4 simply changes to "closed" form in EPANET to model the pipe failure.

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10 ***2-2-Resilience analysis***

11 In this paper, the GRA approach is adopted to evaluate the system resilience under different
12 pipe failure modes (Diao et al. 2016). The possible failure modes were modelled with
13 increasing the stress magnitude and estimating the corresponding strains (Johansson 2007).
14 Different combinations of pipe failure are considered as stress magnitude and ratio of
15 unsupplied demand to total demand is defined as strain magnitude.

16 Due to huge number of possible combinations (a system with N component and m
17 simultaneous failures has $\sum \frac{n!}{m!(n-m)!}$ potential failure scenarios), it is not possible to
18 model every conceivable scenario for each system failure magnitude (Sweetapple et al.
19 2018). For any given stress magnitude, an appropriate affordable number of failure scenarios
20 must be determined. Where the total number of scenarios (*TNS*) is determined as follows
21 (Diao et al. 2016):

$$TNS = \begin{cases} 1, & \text{if } c = c_f \\ c, & \text{if } c_f = 1 \\ \frac{N \times P \times (1-P)}{\left(\frac{CI}{Z_\alpha}\right)^2 \times (N-1) + P \times (1-P)} + 2[c - (c_f - 1)], & \text{if } 1 < c_f < c, \end{cases} \quad (1)$$

1 where, c is the total number of components and c_f shows the number of failed
2 components. N , is the number of possible scenarios for a failure mode and P the probability
3 of success. A value of $P=0.5$ is assumed to provide the minimum sample size required. CI is
4 the confidence interval and Z_α the normal distribution value for a given confidence level. The
5 number of targeted scenarios in each failure mode, is all combinations of 20% of the pipe that
6 produced the highest and lowest supply shortage in the previous step. The random failure
7 scenarios are picked among those pipes whose failure do not result to the lowest or greatest
8 strain.

9 EPANET2 hydraulic solver is used to determine the hydraulic and water quality
10 conditions in a pressurized WDS (Pathirana 2010). As a demand-driven model, EPANET2
11 determines the nodal pressures by considering the specified demand at nodal points (Rossman
12 2000). To illustrate actual supplied water to customers in abnormal conditions, the available
13 nodal demand is expressed as a function (Eq. 2) of nodal pressure head (Wagner, Shamir, and
14 Marks 1988).

$$q_i(t) = \begin{cases} 0, & \text{if } P_i(t) \leq 0 \\ Q_i(t) \sqrt{\frac{P_i(t)}{P_{\min}}}, & \text{if } 0 < P_i(t) < P_{\min} \\ Q_i(t), & \text{if } P_i(t) \geq P_{\min} \end{cases} \quad (2)$$

15 where $Q_i(t)$ is the nodal demand expected to be supplied at junction i at time t ; $P_i(t)$ is
16 the actual pressure at junction i at time t ; P_{\min} is the minimum allowed pressure at junction i

1 (in this paper it is considered as 20 m for nodes with specified demand, and 0 m for nodes
 2 without); $q_i(t)$ is the estimated actual supplied nodal demand at junction i at time t .

3 The strain magnitude is distinguished by calculating dD_f , the ratio of unsupplied
 4 demand to the total demand during strain duration (Eq. 3). The strain duration is the time
 5 between the first occurrence of supply failure and the final return to a non-failure mode (Diao
 6 et al. 2016).

$$dD_f = \frac{\sum_{T_{ss}}^{T_{SE}} \sum_i^N (q_i(t) - q_{if}(t))}{\sum_{T_{ss}}^{T_{SE}} \sum_i^N q_i(t)} \quad (3)$$

7 where $qi(t)$ is the estimated actual supplied nodal demand at junction i at time t when
 8 there is no pipe failure; $q_{if}(t)$ is the estimated actual nodal demand at junction i at time t in
 9 failure scenario f ; T_{SS} : start time of the strain (unsupplied demand); T_{SE} : end time of the
 10 strain; N : the total number of junctions.

11 **2-3- Implementation algorithm**

12 A computer code was developed based on Eqs. 1-3, to implement the global resilience
 13 analysis method for pipe failure. The code calls the EPANET2 engine for hydraulic
 14 simulation (demand-driven) of the failure scenarios (Rossman 2000). The code estimates the
 15 demands at each node in the next step (by Eq 2). This process continues until there is no
 16 significant change in the node pressure (Pathirana 2010). To determine the impact of valves
 17 density on resilience of system to pipe failure, a WDS with three different isolation valve
 18 configuration (i.e., N Valves, N-1 Valves and limited valves is considered. The isolation
 19 segments are identified based on the algorithm presented in previous section. The resilience
 20 analysis of the network is evaluated based on an algorithm presented in Figure 3.

21 **3-Case study**

1 The Net3 network was considered to evaluate the effect of isolation valves on resilience
2 analysis. This case study was used as a benchmark network in global resilience analysis by
3 Diao et al. (2016). Based on suggested guidelines for valve placement, the spacing between
4 two valves should be less than 500 ft in business area, less than 800 ft in other areas (Lakes
5 and Board 1992; Mays 2000; Rosenthal et al., 2002). At least two valves at a T-junction and
6 three at cross sections and no more than four valves for segment isolation should be
7 implemented. Therefore, three different valve configurations are considered for Net3. The
8 valves location in the Limited valve configuration was selected based on suggested guidelines
9 and engineering judgment. The properties and configurations are summarized in Figure 4 and
10 Table 1.

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13 **4-Results and discussion**

14 In this section, to show the effect of connecting reservoir pipes (CRPs) to the distribution
15 network on network resilience, these pipes were analysed first. Then the system resilience
16 with three different valve configurations are discussed.

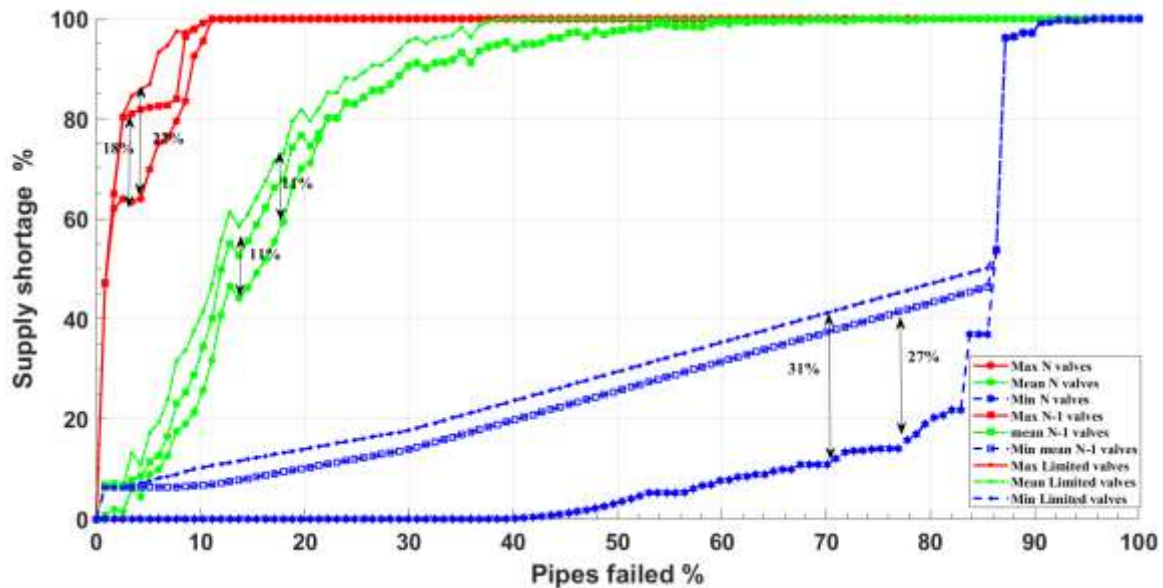
17 ***4-1- Resilience of CRPs***

18 In Figure 5 the resilience of Net3 for two approaches (i.e., whole network (WN), and network
19 without CRP (NWCRP)) are compared. The GRA showed that Net3 encountered complete
20 failure due to simultaneous failure of the four main CRPs. Whereas excluding these pipes
21 from the resilience analysis showed that the failure of 12 pipes lead to the complete supply
22 failure. The maximum and average network supply shortage were 36% and 12% higher than
23 the whole network model. The supply shortage for all combinations of CRP failures in the
24 peak demand period (18-20 pm) is presented in Figure 6. Based on this analysis, the most

1 critical pipes are 1, 4, 2, 3, 5 (pipes connected to tank 3, the river, tank 1, tank 2 and the lake,
 2 respectively). Since the pumping from the lake did not occur during this period, pipe 5
 3 acquired the least priority. The supply shortage for different combinations of CRP failures is
 4 illustrated in Figure 7. Duplication of these four main pipes, can enhance the network
 5 resilience up to 36%.

6 **4-2- Valve configuration effects**

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10 Figure 8 shows the GRA curves of the three different arrangements of isolation valves in
 11 Net3. The CRPs were excluded in these analyses. The maximum, mean and minimum
 12 resilience of Net3 for N valves configuration was about 18%, 11%, and 27% higher than the
 13 N-1 valves configuration. The resilience in limited Valves configuration, is about 22%, 11%,
 14 and 31% lower than the N valves in the maximum, mean and minimum, respectively. Thus,
 15 by adding approximately 50 valves to the network (converting the limited valves to the N-1
 16 valves configurations) the network resilience increased up to 22%.

17 It should be noted that the critical pipes of Net3 varied by different valve configurations
 18 (Table 2). Pipe 233 connected to node 203 with highest demand, is the most critical pipe in

1 all three configurations. While other critical pipes of the N valves configurations did not
2 coincide with limited valves and N-1 valves configurations. Thus, the actual location of
3 isolation valves significantly changed the critical pipes of the network (

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10 **4-3- Interventions to enhance the resilience**

11 To enhance the resilience of the network addition of isolating valves to the critical segments
12 could be considered. For example, in the limited valves configuration, by adding 4 isolation
13 valves to the critical segments and converting these segments into smaller segments as shown
14 in Figure 12, the resilience increased by 6%.

15 Figure 13Figure 14 represents the number of isolation valves and pipes in each
16 segment for N-1 and limited valves configurations. In the N valves configurations, most
17 network pipes have two isolation valves except the branch pipes that have one isolation
18 valve. Table 3 and Table 4 represents the mean and maximum values of network supply
19 shortage for all valve configurations. The most critical segments of N-1 and limited valves
20 configurations are 41 and 13, respectively. Neither of these two segments has the maximum
21 number of pipes and valve, but they have the maximum nodal demand.

22 **5-conclusions**

23 Subsystem isolation is required to repair or to rehabilitate a broken component which is
24 done by closing the adjacent valves. In this study, the effect of valve location on the
25 resilience of WDSs due to pipe failure were analyzed. The resilience of Net3
26 benchmark systems to three valve configurations (N valves, N-1 valves, and limited

1 valves) were evaluated. To model the pipe failure mode, it was necessary to find
2 adjacent isolation valves to each pipe in order to isolate a segment including the failed
3 pipe. A method to divide the network to isolated segments based on isolation valves
4 was proposed. The global resilience analysis method was implemented to find out the
5 critical segments. It was shown that the critical segments varied for different valve
6 configurations. The critical pipes can also be changed in different valve configurations.
7 Therefore, the valve configuration can change the global resilience of a water
8 distribution system. It was demonstrated that the resilience can be enhanced by
9 interventions such as adding isolation valves to the critical segments and converting
10 them into smaller portions so that they could be removed from service without
11 affecting much of the system in emergency circumstances.

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Table 1. Properties of Net3 for different valve configuration

<i>Configuration</i>	<i>Junctions</i>	<i>Pipes</i>	<i>Reservoirs</i>	<i>Tanks</i>	<i>Pumps</i>	<i>Isolation valves</i>	<i>Segments</i>	<i>Demand</i>
<i>Without valves</i>	91	115	2	3	2	0	0	717.3
<i>With N valves</i>	510	327	2	3	2	228	114	717.3
<i>With N-1 valves</i>	302	222	2	3	2	105	80	717.3
<i>With Limited valves</i>	195	167	2	3	2	52	30	717.3

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Table 2. Critical pipes for different valve configurations

<i>Model</i>	<i>Critical pipes ID</i>									
<i>N valves</i>	233	193	247	201	129	330	333	113	125	217
<i>N-1 valves</i>	233	231	323	329	125	122	123	129	315	193
<i>limited valves</i>	233	231	323	317	239	122	123	129	125	329

Table 3. Average supply shortage for all valve configurations

<i>Valve configuration</i>	<i>Average No. of valves for segment isolation</i>	<i>Average No. of pipe in segments</i>	<i>Average supply shortage when one pipe failed (%)</i>
<i>N valves</i>	1.92	1	8.24
<i>N-1 valves</i>	2.58	2.65	9.44
<i>Limited valves</i>	3.1	5	11.9

Table 4. Maximum number of valves in each segment for different valve configurations

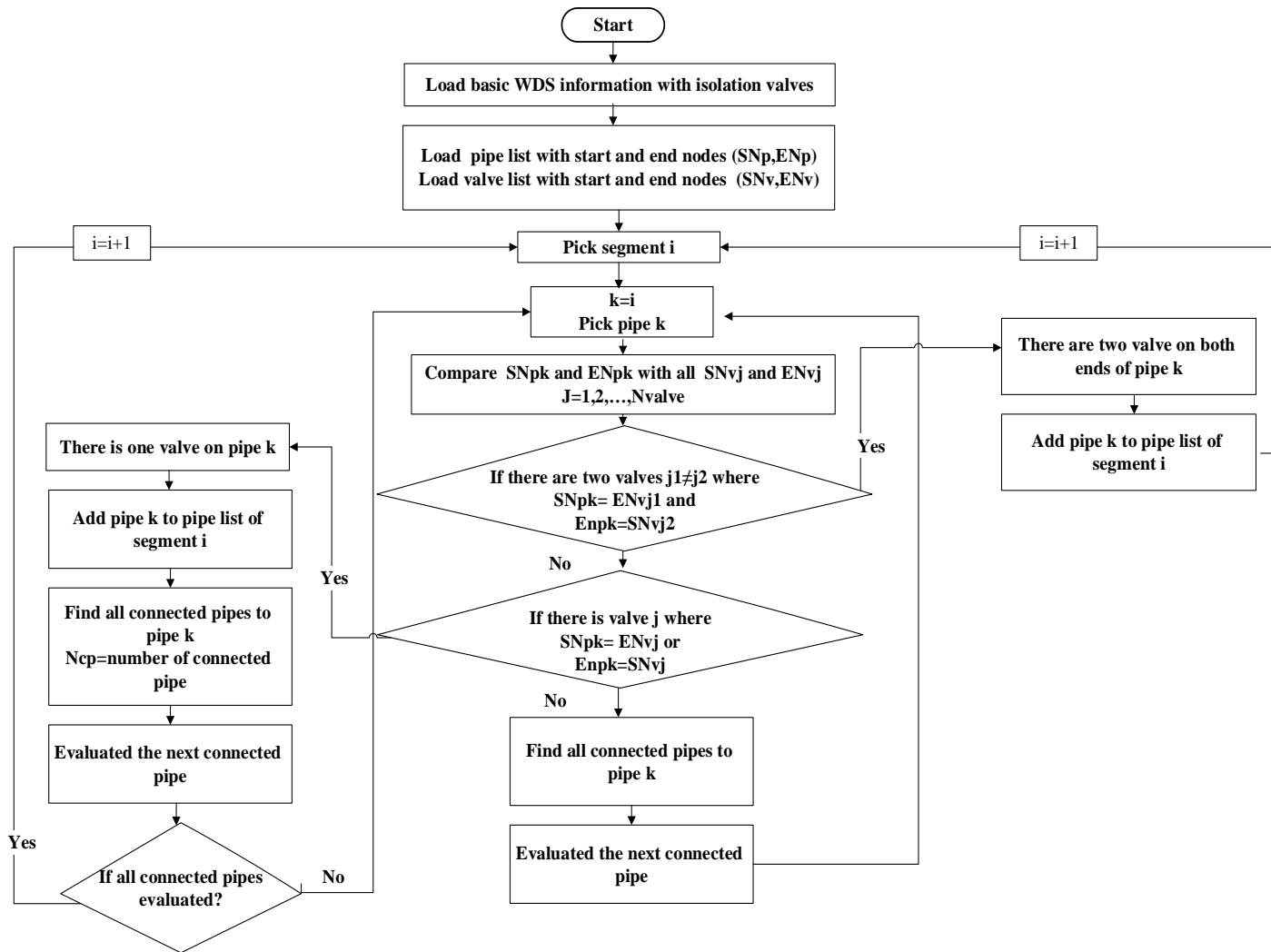
<i>Valve configuration</i>	<i>maximum No. of valves for isolation each segment</i>	<i>maximum No. of pipe in segments</i>
<i>N valves</i>	2	1
<i>N-1 valves</i>	5	6
<i>Limited valves</i>	6	11

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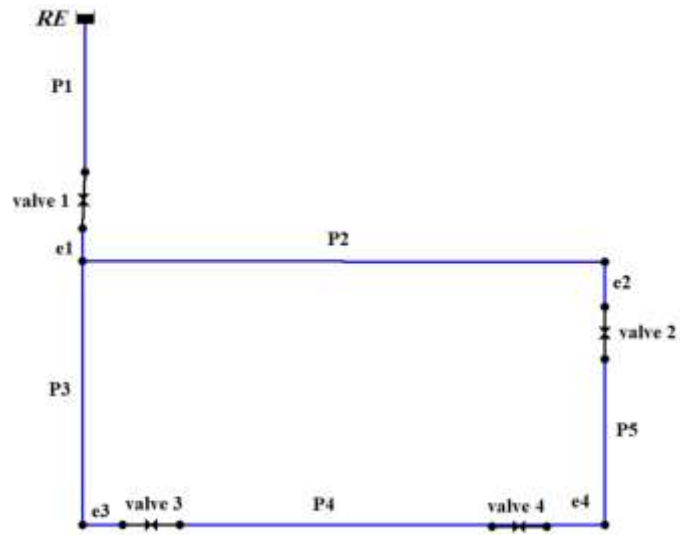
Figure 1. A flowchart to find the adjacent isolation valves of each pipe in a WDS

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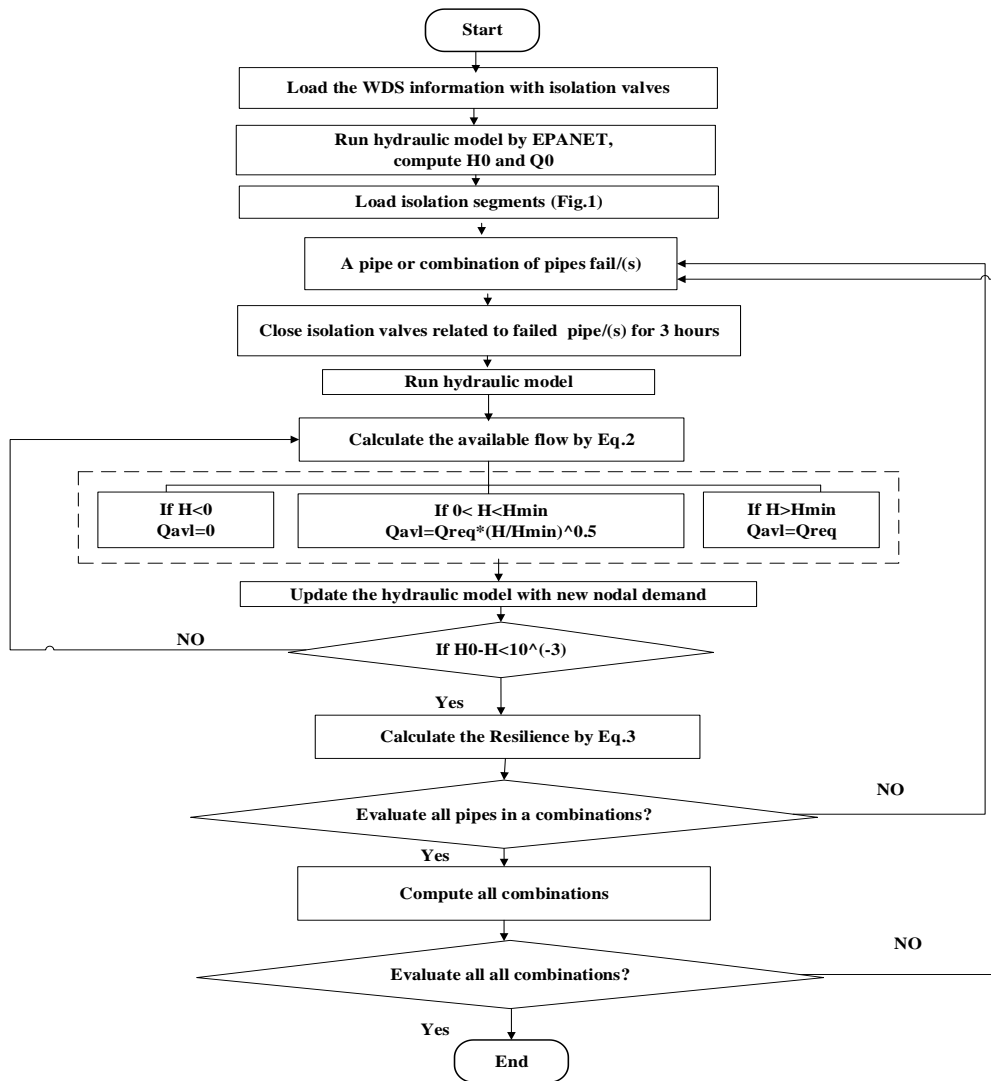
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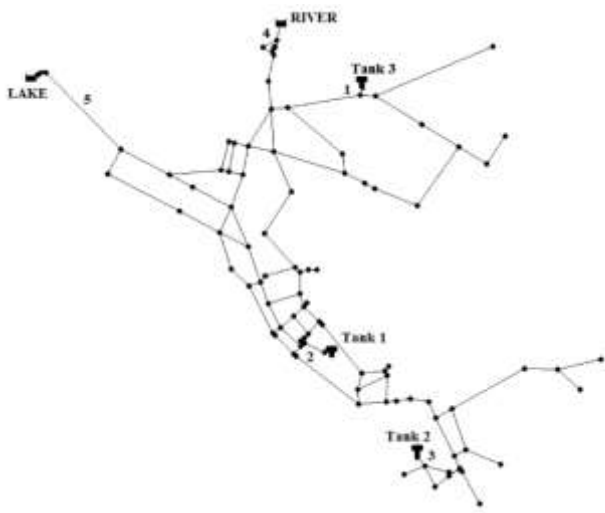
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Figure 2. An example of WDS

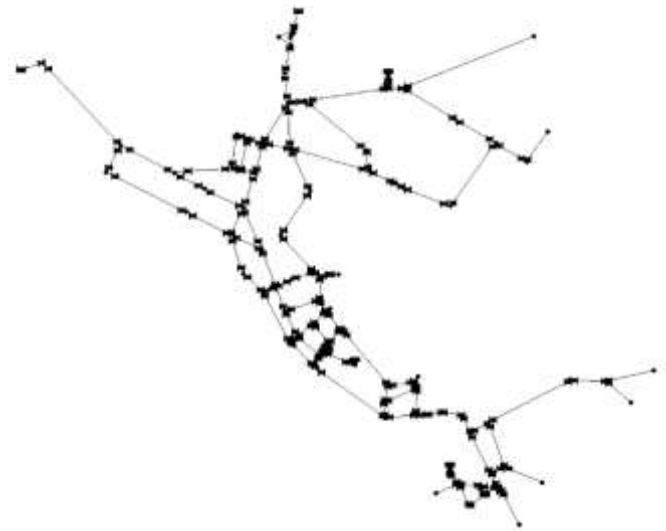


1 Figure 3. The flowchart for resilience analysis of pipe failure in WDS by isolation valves

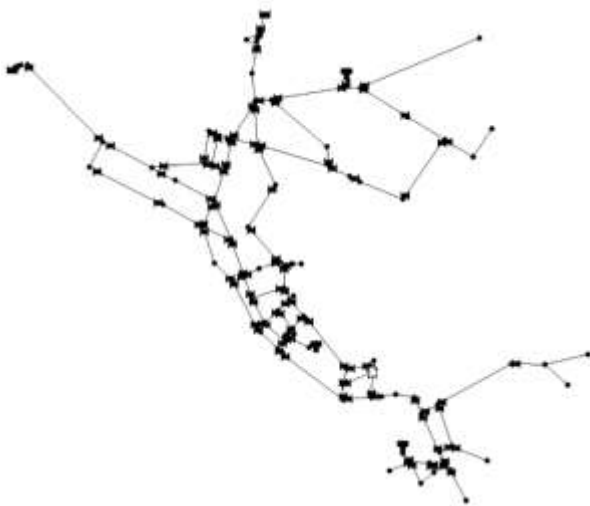
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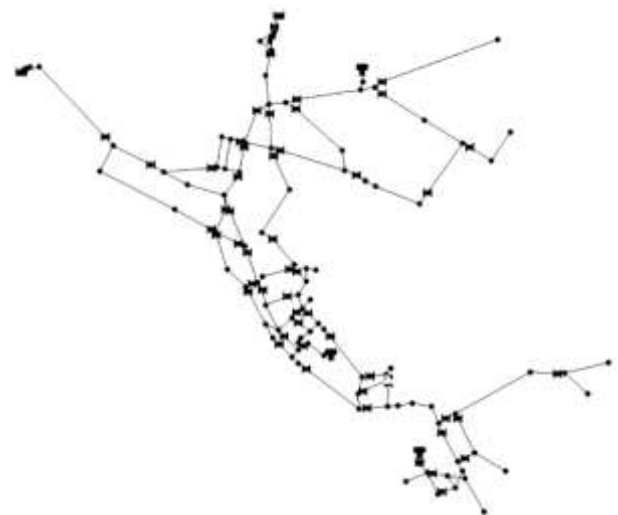
(a)



(b)

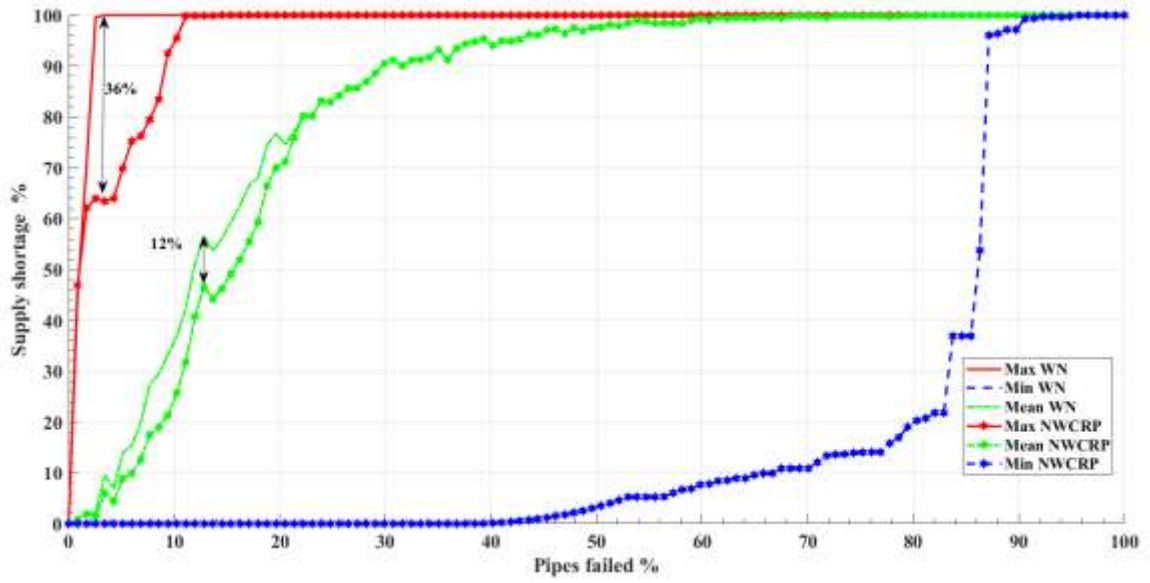


(c)



(d)

Figure 4. a) Net3 without valve b) N valves c) N-1 valves and d) Limited valves configurations



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Figure 5. Supply shortage for the whole network(WN) and the network without CRP (NWCRP))

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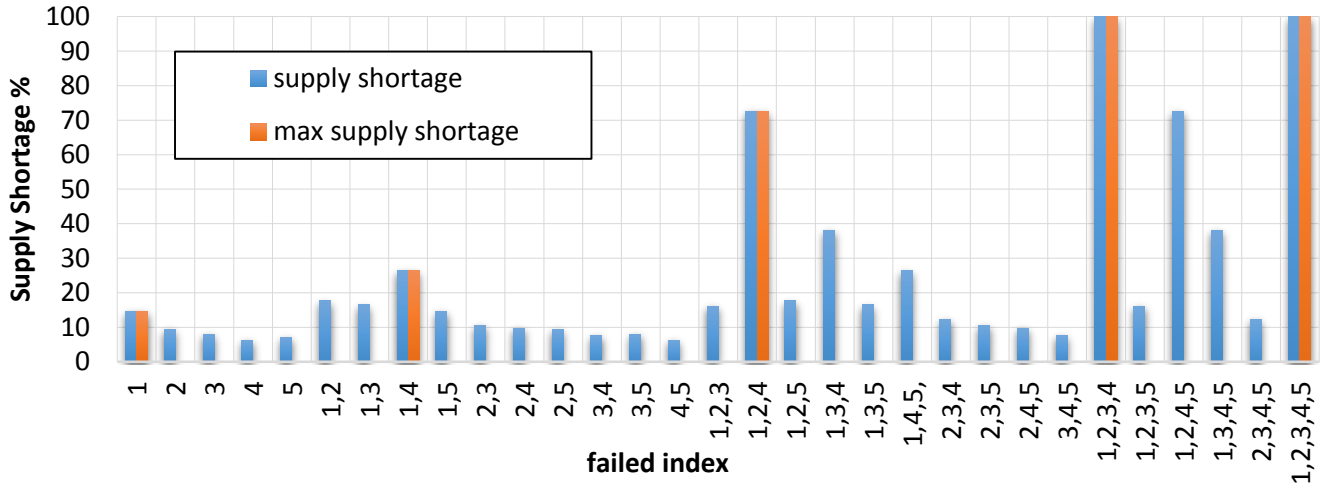


Figure 6. Supply Shortage for all combination of CRP failure

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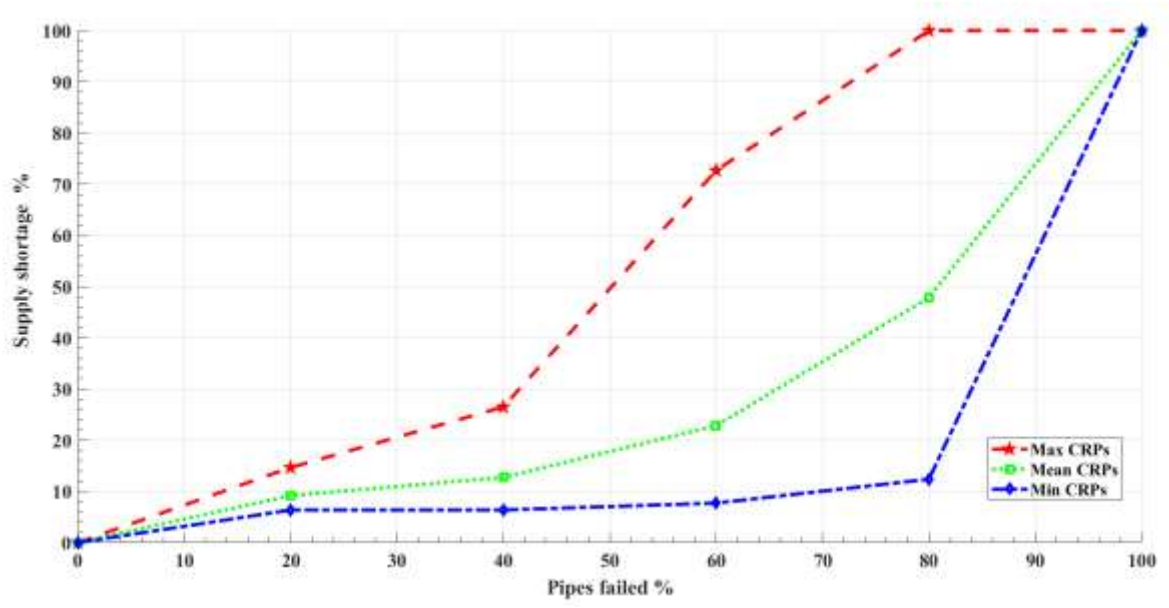


Figure 7. Supply shortage for CRP failures

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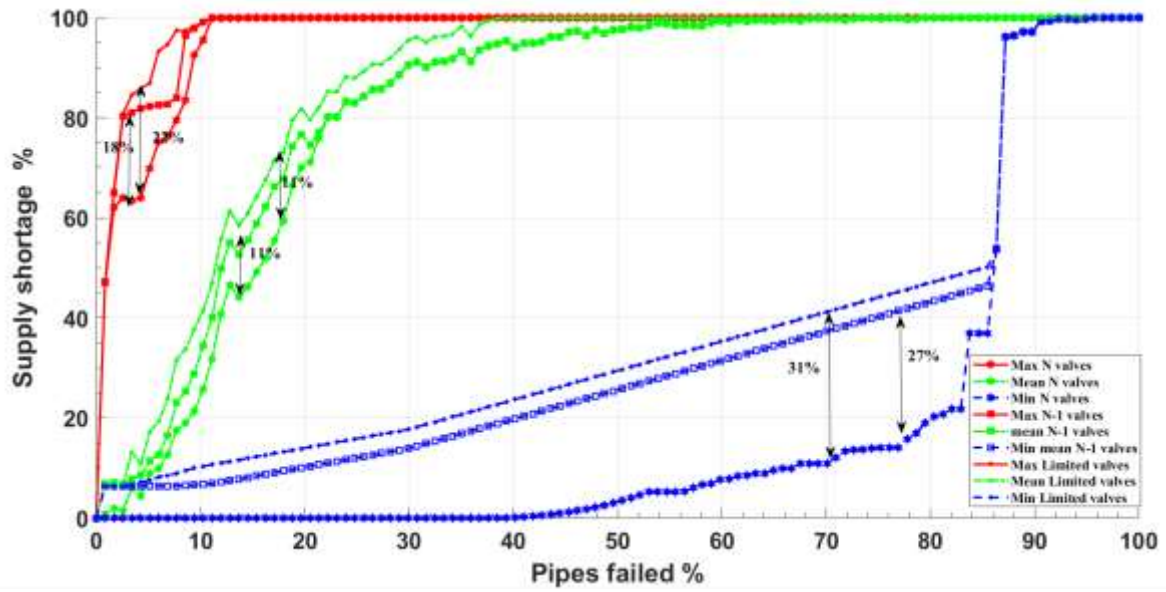


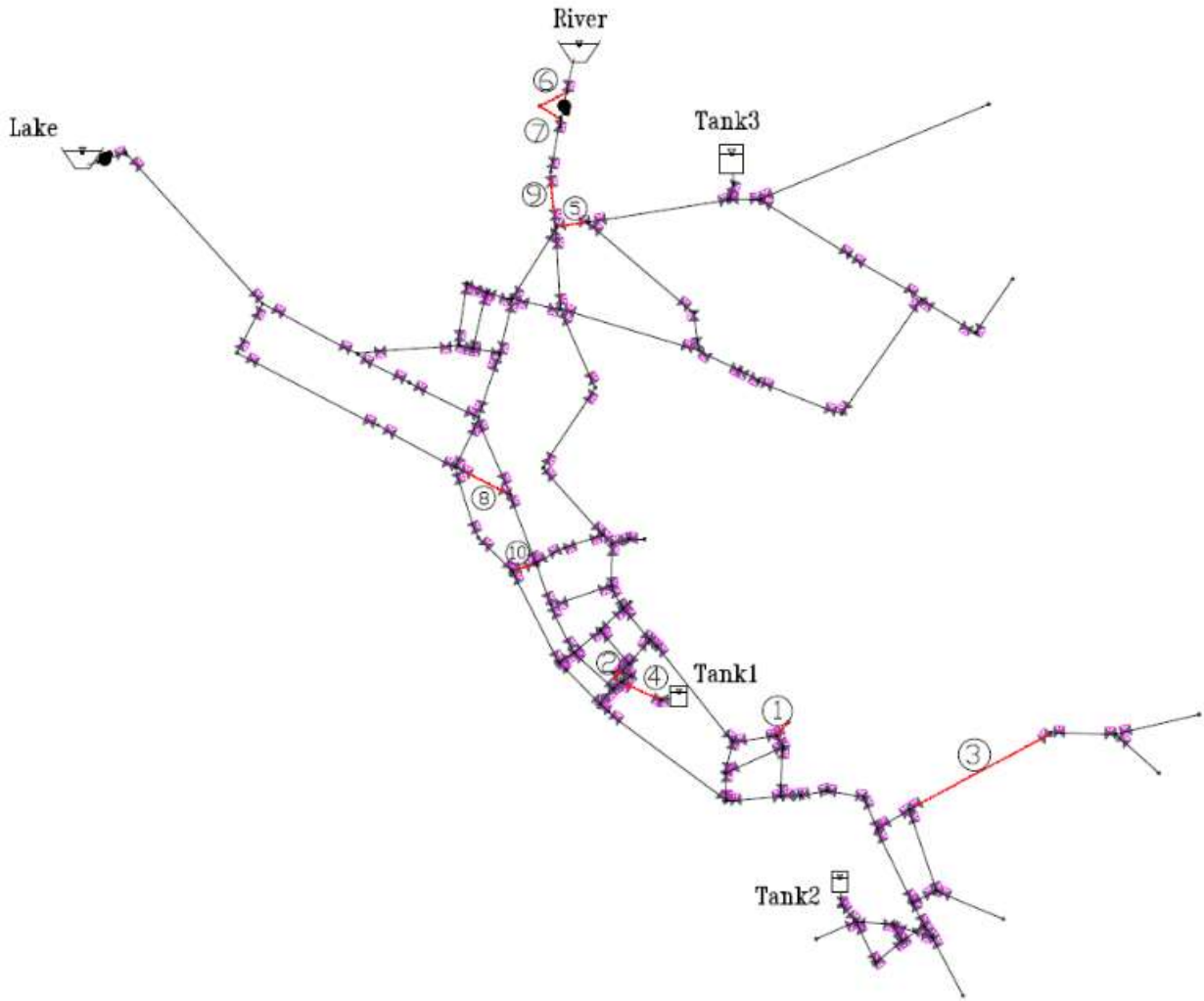
Figure 8. GRA curves for three valve configurations

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Figure 9. Critical pipes in N-valves configurations

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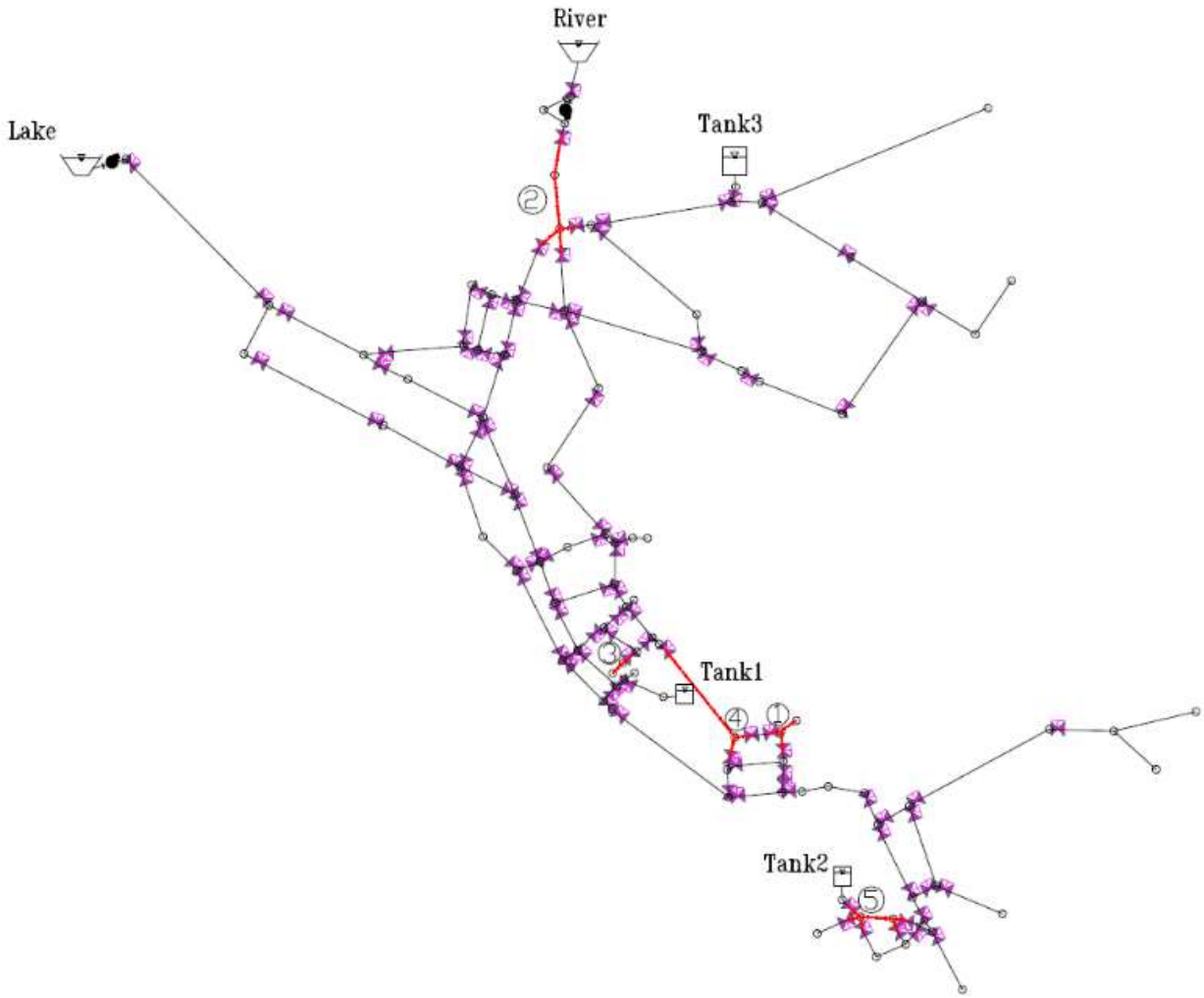
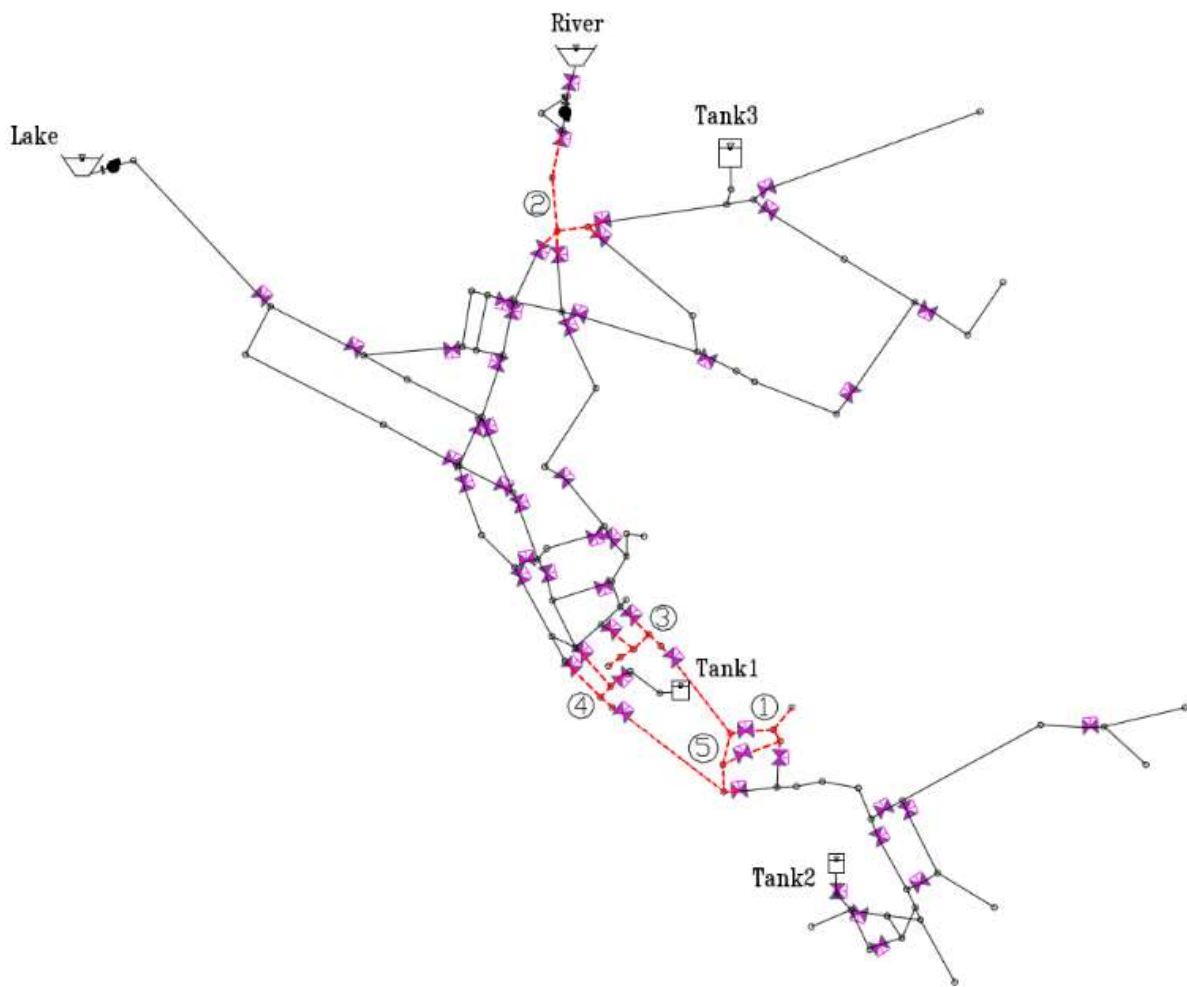


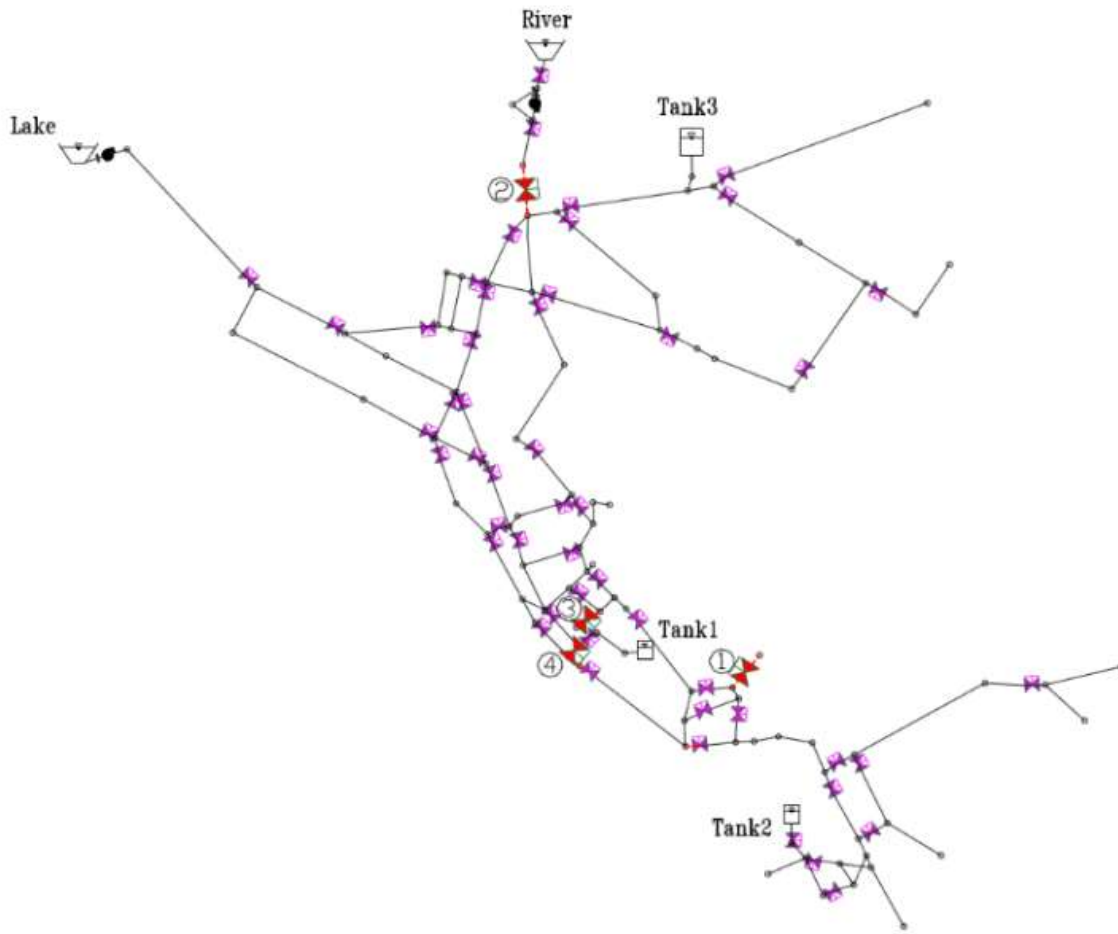
Figure 10. Critical pipes in N-1 valves configurations

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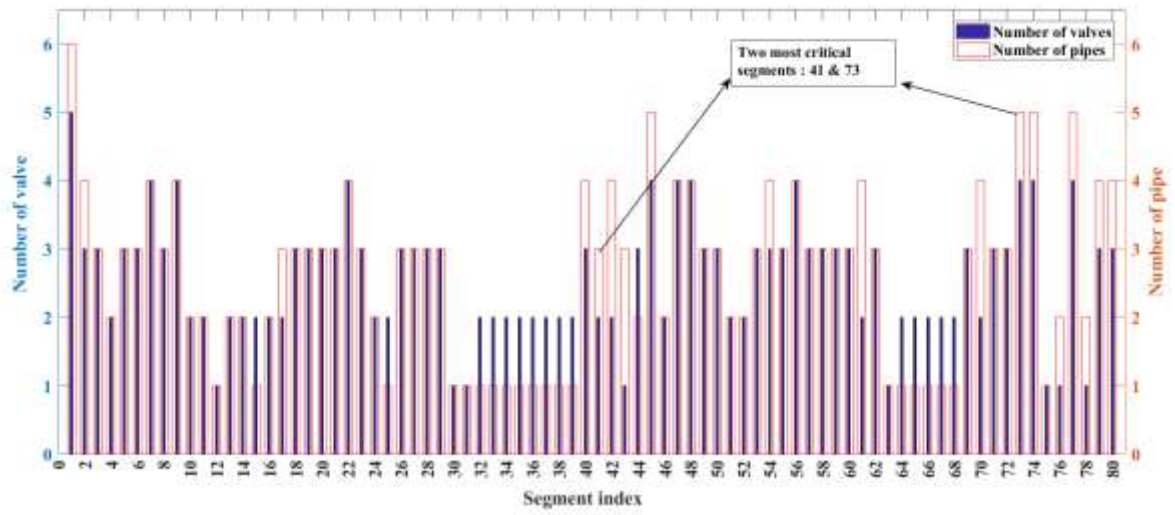
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Figure 11. Critical pipes in limited-valves configurations



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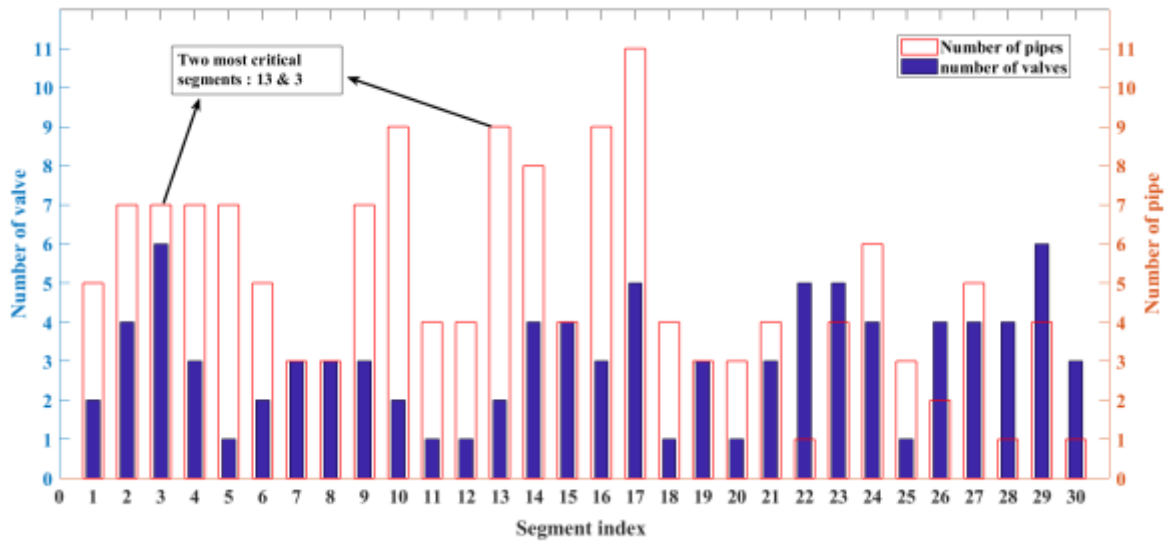
Figure 12. Adding 4 isolation valve to the critical segments in limited valves configurations



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Figure 13. Number of valves and pipes in segment for N-1 valves configurations

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Figure 14. Number of valves and pipes in segment for limited valves configurations