

# Performance Indicators for Damaged Water Distribution Systems

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**Abstract:** Water distribution systems are one of the most vital lifelines of urban areas. A water distribution system consists of pipes and other hydraulic appurtenances like valves, pumps, connection fittings and storages. Pipes are the main elements of a water distribution system and they may be damaged after natural disasters (earthquake, landslide etc.) or operational errors (waterhammer etc.). Pipe damages are grouped as breaks and leaks. A water distribution system is expected to serve at a certain level after some pipes were damaged. Performance of a water distribution system depends on the available flows and pressures in the damaged system. Performance indicators may be grouped into four levels. Earthquake is the major destructive phenomenon on the water distribution systems so in this study post-earthquake performance of a hypothetical water distribution system will be examined in detailed. Some performance indicators for water distribution systems are presented here and calculated for a hypothetical water distribution system. Graphical Iterative Response Analysis for Flow Following Earthquakes (GIRAFFE) computer program was used with EPANET to perform deterministic and Monte-Carlo probabilistic simulations of the system. The performance of a hypothetical water distribution system was evaluated with probabilistic performance indices and graph based network metrics. Node demand satisfaction and graph based network metrics were compared.

**Key words:** Water Distribution System, Earthquake, Reliability, Serviceability, GIRAFFE

## 1. INTRODUCTION

A water distribution system (WDS) is one of the critical lifeline systems in urban areas. Past earthquakes have demonstrated that WDSs are vulnerable to earthquakes. The failure of a WDS not only impairs fire fighting capacity, but also disrupts residential, commercial, and industrial activities, resulting huge economic losses. Hence, it is important to assess the seismic performance of a WDS (Hwang et al., 1998).

Lifelines are usually configured as networks. For example, water distribution networks in which customers and water treatment plants are interconnected by pipelines, control valves, pumps, tanks and reservoirs. Damage to lifelines not only results in physical impairment and cost of repair at specific locations, but also the losses of connectivity and potential for more widespread and serious losses of functionality throughout the network (Wang and O'Rourke, 2008).

Post earthquake serviceability of WDSs of some cities and hypothetic systems were studied in the literature. Javanbarg and Takada assess the seismic reliability of Osaka City after the 1995 Kobe earthquake using availability and serviceability indices (Javanbarg and Takada, 2010). Chou and others examined the serviceability of the Lan-Yan area in Taiwan after soil liquefaction by means of GIRAFFE software (Chou et al., 2013).

In this study, damage concepts of a WDS was investigated, pipe damage modeling and negative pressure treatment were described. Then Monte Carlo (MC) simulation technique in the pipe damage process was explained. Probabilistic and graph based performance evaluation methods of damaged water distribution networks were discussed. As a case study, earthquake performance of a

hypothetical water distribution system examined with both techniques. By using graph connectivity and expansion properties, system robustness against pipe failures was assessed.

## 2. METHODS

Earthquake damage to buried pipelines can be attributed to transient ground deformation (TGD) or to permanent ground deformation (PGD) or both. TGD occurs as a result of wave propagation or ground shaking effects while PGD occurs as a result of surface faulting, liquefaction, landslides and differential settlement from consolidation of cohesionless soils. The relative magnitudes of TGD and PGD determine which will have the predominant influence on pipeline response (Toprak et al., 2009). The effects of TGD and PGD are evaluated for the components of above ground and underground facilities of WDS. The underground facilities performance under seismic loading is assessed by models for soil-structure interaction, including empirical models based on the observations from the past earthquakes, closed form analytical methods and numerical simulations such as finite element analysis. To account for uncertainty with respect to component or facility response, seismic behavior is frequently characterized by fragility curves that provide the probability of failure as a function of demand (Peak Ground Acceleration, Peak Ground Velocity etc.). Fragility curves can be derived from either the observations of past earthquakes or MC techniques that have special capability in quantifying uncertainty (Wang and O'Rourke, 2008). PGD hazards are usually limited to small regions with high damage rates due to the large deformation imposed on pipelines. In contrast the TGD hazards typically affect the whole pipeline network, but lower damage rates (Shi and O'Rourke, 2008). In this study WDS damage is represented by only with pipe damages, earthquake effects on the other components of the WDS like pumping and storage facilities were not taken into consideration. Pipe damages were calculated with repair rate (RR) (repairs/km).

### *2.1 Pipe Damage Modeling*

Water supply systems provide water to customers at the desired flow rate and pressure. Carrying water from source to customer requires a network consists of reservoirs, tanks, pipes, pumps, valves etc. In a real WDS water is withdrawn along a pipe but in the mathematical model pipe junctions are accepted as consumption points. A hydraulic network is a mathematical model of a WDS in which the physical components are represented as nodes and links. Pipes are represented by links in the hydraulic network, junctions of the pipelines are represented by nodes and they accepted as water discharge points to the customers. In the event of an earthquake a WDS may sustain various kinds of damage, previous research shows that buried pipelines in a WDS are the most vulnerable components (ATC, 1991) so, in this study pipe damages will be taken into consideration as system damage. Pipe damages may be grouped into two as break and leak.

In this study Graphical Iterative Response analysis for Flow Following Earthquakes (GIRAFFE) software and its methodology of pipe damage simulation and negative pressure elimination will be used. GIRAFFE is developed at Cornell University dedicating for the hydraulic analysis of the damaged water supply systems (Cornell University, 2007). GIRAFFE works iteratively with the EPANET which is a computer program that performs extended period simulation of hydraulic and water quality behavior within pressurized pipe networks (EPA, 2000).

#### *2.1.1 Pipe Break*

A break is defined as the complete separation of a pipeline, such that no flow will pass between the two adjacent sections of the broken pipe. In case of the break, water flows from the two broken ends into the surrounding soil. In GIRAFFE the broken pipe is modeled by using the EPANET elements as a fictitious pipe and reservoir are attached at each broken end of the pipe, check valves

ensure that water only flows from the broken pipe into the reservoirs which are fixed at atmospheric pressure to simulate the broken pipe being open to the atmosphere (Cornell University, 2007).

### *2.1.2 Pipe Leak*

A leak is defined as a gap in pipe, such that water will continue to flow through the pipeline, while some loss of pressure and flow through the leak. In GIRAFFE leakage is simulated by a fictitious pipe open to the atmosphere, simulated as an empty reservoir with the same elevation as the leak location. A check valve constrains flow from the leaking pipe in one direction. The roughness and minor loss coefficients of the fictitious pipe are taken as infinite and 1, respectively, such that all energy loss from the leak is related to the minor loss (Cornell University, 2007). Since a leak is modeled as a fictitious pipeline in hydraulic network analysis in GIRAFFE, the area of this pipeline should be calculated from the equivalent orifice diameter. GIRAFFE classifies leaks into five scenarios as annular disengagement, round crack, longitudinal crack, local loss of pipe wall and local tear of pipe wall which are frequent leak types for metallic pipes. Equivalent orifice area equations for each leak type can be found in the GIRAFFE manual (Cornell University, 2007). Probabilities of the leak scenarios are dependent to the pipe material. In this study pipe material is accepted as ductile iron and default leak type probability values for this material in GIRAFFE are annular disengagement 80%, longitudinal crack 10% and local loss of pipe wall 10%; round crack and local tear of pipe wall type cracks are not expected for ductile iron pipes.

### *2.1.3 Negative Pressure Treatment*

Hydraulic network analysis solves incompressible water flow in a pressurized pipeline network based on two principle laws: conservation of mass and conservation of energy. The conventional hydraulic network analysis algorithm does not differentiate positive and negative pressures and only uses the total head difference to drive water flow to satisfy demands. Commercial hydraulic network analysis software packages are designed for undamaged systems. The forced satisfaction of all demands may lead to the prediction of unrealistically high negative pressures at some nodes. Water distribution systems are not air tight so that their ability to support negative pressures is very limited (Shi and O'Rourke, 2008).

In GIRAFFE, an isolation approach is applied to treat the negative pressures. This isolation approach works with EPANET hydraulic network engine iteratively. After hydraulic network analysis of the damaged system using EPANET engine, nodes with negative pressures are identified and isolated step by step, starting with the node of highest negative pressure. After each elimination, network connectivity is checked. If part of the system is isolated from the main system without water sources, it is taken out of the system. Flow analysis and the elimination process continue until no negative pressure nodes exist in the system (Cornell University, 2007).

## **2.2 MC Simulation**

To simulate the earthquake performance of a WDS, pipe damage, including breaks and leaks, needs to be added in the network. Hydraulic simulation is then performed on the damaged network to predict the flow and pressure distributions. In GIRAFFE the pipeline break and leak models can be implemented into a hydraulic network both deterministically and probabilistically. The deterministic implementation specifies the number and location of leaks and breaks, and the orifice area of each leak, occurring in a pipeline network. This implementation can be used to simulate the performance of a WDS under a specific damage scenario. Whereas damage type and place has a probabilistic character even the RR of the pipes are known. The probabilistic implementation generates randomly distributed pipe damage in the system according to pipeline repair rate. Three normally distributed random numbers are used to determine the place of the damage, state of the damage (break or leak) and the leak type if it is a leak. In HAZUS (NIBS, 1997) it is recommended

that 80% and 20% of earthquake damage occurs as leaks and breaks, respectively, under seismic wave effects. With GIRAFFE, users have the ability to set the percentages of leaks and breaks to values other than the default settings of 80% and 20%, respectively (Cornell University, 2007).

### 2.3. Evaluation Methods for WDS Performance

The probabilistic implementation applied many times by using MC simulation to show the random character of damage. In GIRAFFE, number of MC simulations can be specified by user (MC Fixed Number) or automatically determined according to the user-specified convergence criteria (MC Flexible Number). Reliability assessment of water networks comprises a complex, yet essential process. The seismic reliability of water networks is possible to be measured using different indices of physical nature or not, like vulnerability, connectivity, serviceability, maximum flow, redundancy and economic loss (ATC, 1992). The seismic performance evaluation methods can be classified into four levels (SYNER-G, 2011):

- Level I (Vulnerability Analysis): The aim of this analysis is to estimate the percentage of the physical damages in a specific region. The performance index used in Level I studies is the “Damage Ratio” that describes the expected number of failures per unit length or percentage of the damaged links of the system. In this study RR will be used as the Level I performance index which is the damage (break or leak) number per kilometer of pipelines in the system.
- Level II (Connectivity Analysis): In a second stage the damaged components should be removed from the network. A simple connectivity analysis of the network can be accomplished using Graph Theory and Statistical Methods. In this study average path length, betweenness, degree, diameter, density and spectral radius of damaged and undamaged water distribution network are used as Level II performance indicators.
- Level III (Flow Analysis): Heads at the nodes and flow rates at the pipes are calculated before and after earthquake conditions. The performance indexes used in Level III analyses account the probability distribution of the percentage of customers who would lose their service after a specific earthquake. Head ratio may be used as a Level III performance indicator. For each node, this index is defined as the ratio of the water head in the seismically damaged network to the reference value for pre-earthquake normal operations conditions. The determination of the water head requires a flow analysis on the network. This index expresses a functional consequence in the  $i^{\text{th}}$  component of the physical damage to all system components.
- Level IV (Serviceability Analysis): Vulnerability estimation of water system components beside with a flow analysis is repeated for different seismic intensities using Monte-Carlo simulations. In this study Serviceability Index will be used as the Level IV performance indicator which is defined as the ratio of the available demand to required demand corresponding to a seismic damage scenario. GIRAFFE uses serviceability as the performance index of the earthquake damaged water distribution network in Equation (1).

$$S_s = \frac{Q_T}{Q_T^*} \quad (1)$$

where,  $S_s$  is the serviceability,  $Q_T$  is the available demand and  $Q_T^*$  is the required demand. The serviceability for the entire system is the sum of the demands that can be satisfied over the sum of the total required demands. For each MC simulation run, the serviceability is reported by GIRAFFE for each demand node and for the entire system.

## 2.4. Probabilistic Performance of WDSs

A consumer of a water supply system is represented as a node  $i$  with water demand  $Q_i$  in a hydraulic network model. System Serviceability Index (SSI) defined as the ratio of sum of the satisfied customer demands after an earthquake to that before earthquake in Equation (2).

$$SSI_i = \frac{\sum_{i=1}^n Q_i}{\sum_{i=1}^{n_0} Q_i} \quad (2)$$

where,  $n$  and  $n_0$  are the number of satisfied demand nodes after and before the earthquake. The water supply reliability for the consumer  $i$  can be measured by the probability,  $P(Q_i)$ , of  $Q_i$  satisfied. Two probabilistic measures associated with the water demand a node  $i$ , Damage Consequence Index ( $DCI_{ij}$ ) and Upgrade Benefit Index ( $UBI_{ij}$ ), are defined to measure the impact of a Pipe  $j$  on the reliability of water supply to a consumer  $i$  and to identify critical links that significantly affect the  $P(Q_i)$ . The  $DCI_{ij}$  for pipe  $j$  is defined to reflect the consequence from damaging the pipe as shown in Equation (3).

$$DCI_{ij} = \frac{P(Q_i) - P(Q_i|L_j)}{1 - P(Q_i)} \quad (3)$$

in which,  $P(Q_i|L_j)$  is the conditional probability of  $Q_i$  satisfied, given that Pipe  $j$  is damaged.  $DCI_{ij}$  is the percent reduction of  $P(Q_i)$ , given that Pipe  $j$  is damaged (Wang and Au, 2009). The  $UBI_{ij}$  for Pipe  $j$  is expressed in Equation (4).

$$UBI_{ij} = \frac{P_{upgrade_j}(Q_i) - P(Q_i)}{1 - P(Q_i)} \quad (4)$$

in which,  $P_{upgrade_j}(Q_i)$  is the conditional probability of  $Q_i$  satisfied in a system where Pipe  $j$  is “upgraded” or damage occurrence probability to be zero.  $UBI_{ij}$  is the percent increase of  $P(Q_i)$ , given that Pipe  $j$  is upgraded.  $DCI_{ij}$  can be effectively estimated as shown in Equation (5).

$$DCI_{ij} = \frac{\frac{n_1}{m_1} - \frac{n_3}{m_3}}{1 - \frac{n_1}{m_1}} \quad (5)$$

in which,  $m_1$  is the number of all MC simulations under the nominal scenario,  $n_1$  is the number of MC simulations in  $m_1$  that  $Q_i$  is satisfied,  $m_3$  is the number of MC simulations that damage is observed in pipe  $j$ ,  $n_3$  is the number of MC simulations in  $m_3$  that  $Q_i$  is satisfied.  $UBI_{ij}$  can be effectively estimated as shown in Equation (6).

$$UBI_{ij} = \frac{\frac{n_2}{m_2} - \frac{n_1}{m_1}}{1 - \frac{n_1}{m_1}} \quad (6)$$

in which,  $m_2$  is the number of MC simulations that no damage occurs in pipe  $j$  and  $n_2$  is the number of MC simulations in  $m_2$  that  $Q_i$  is satisfied (Wang and Au, 2009).

## 2.5 Graph Based Water Distribution Network Metrics

The theory of complex networks employs techniques from graph theory and statistical physics to classify different network models, to analyze their structural complexities and quantify the vulnerability, robustness and damage tolerance of the networks. A network is represented as a mathematical graph set of graph vertices with  $n$  elements and graph edges set of  $m$  elements. In case of the WDS vertices are demand nodes or pipe intersections and edges are pipes. Water distribution

systems could be potentially weighted bi-directional networks but in this study the hypothetical network is treated as an undirected and unweighted graph (Yazdani and Jeffrey, 2011).

Among in many structural metrics being used in the literature to assess redundancy and robustness of networks, in this study average path length, diameter, density, spectral radius values will be used for the system level, betweenness and degree will be used for node level network metrics.

Average path length ( $l$ ) of a network is the average value of the geodesic distances between all pairs of nodes as shown in the Equation (7).

$$l = \frac{1}{n(n-1)} \sum_{(ij)} d_{ij} \quad (7)$$

where,  $n$  is the number of nodes,  $d_{ij}$  is the shortest distance between the nodes  $i$  and  $j$ . If there is no path between two vertices then  $d_{ij}$  becomes zero. Diameter of a network ( $d$ ) is the maximum geodesic length of the shortest path between all pairs of nodes as shown in the Equation (8). The diameter characterizes the ability of two nodes to communicate with each other. The smaller  $d$  is, the shorter is the expected path between nodes (Albert et al., 2000).

$$d = \max(d_{ij}) \quad (8)$$

The density of a graph ( $q$ ) is the ratio of the number of edges and the number of possible edges can be calculated as shown in the Equation (9).

$$q = \frac{2m}{n(n-1)} \quad (9)$$

where,  $m$  is the number of edges and  $n$  is the number of nodes. The spectral radius of a graph ( $\rho$ ) is the largest nonzero eigenvalue of graph's adjacency matrix and can be calculated as shown in Equation (10). The adjacency matrix of a graph is a matrix with rows and columns labeled by graph vertices, with a 1 or 0 according to whether vertices are adjacent or not respectively. For a simple graph without self-loops, the adjacency matrix must have 0s on the diagonal. For an undirected graph, the adjacency matrix is symmetric (Lewis, 2009).

$$\rho(A) = \max\{|\lambda_1|, \dots, |\lambda_n|\} \quad (10)$$

where,  $\lambda_1, \dots, \lambda_n$  be the (real or complex) eigenvalues of the adjacency matrix  $A \in \mathbb{C}^{n \times n}$ . Betweenness of a node (vertex) ( $C_B$ ) of a network is defined by the number of geodesics (shortest paths) going through the vertex. The betweenness centrality of a node  $v$  is given by the Equation (11).

$$C_B(v) = \sum_{i \neq v \neq j} \frac{\sigma_{ij}(v)}{\sigma_{ij}} \quad (11)$$

where,  $\sigma_{ij}$  is the total number of shortest paths from node  $i$  to node  $j$  and  $\sigma_{ij}(v)$  is the number of those paths that pass through  $v$ . Degree of a vertex is simply the number of nodes that a given node is connected to.

### 3. RESULTS

Performance indicators of a damaged WDS will be examined by means of a hypothetical WDS in this study. The hypothetical system consists of 51 pipes, 36 pipe junctions (nodes) and a reservoir (Figure 1). Elevations of all junctions are 100 meters and lengths of all pipes are 400 meters. Demand from each node is accepted as 2 liters per second. Water surface elevation of the reservoir

is 160 meters and all pipes are ductile iron with the Williams Hazen roughness coefficient of 130. Pipe diameters are varying from 80 mm to 300 mm as shown in the Figure 1. Although the case WDS is hypothetical, values of the parameters were selected compatible with the regulations.

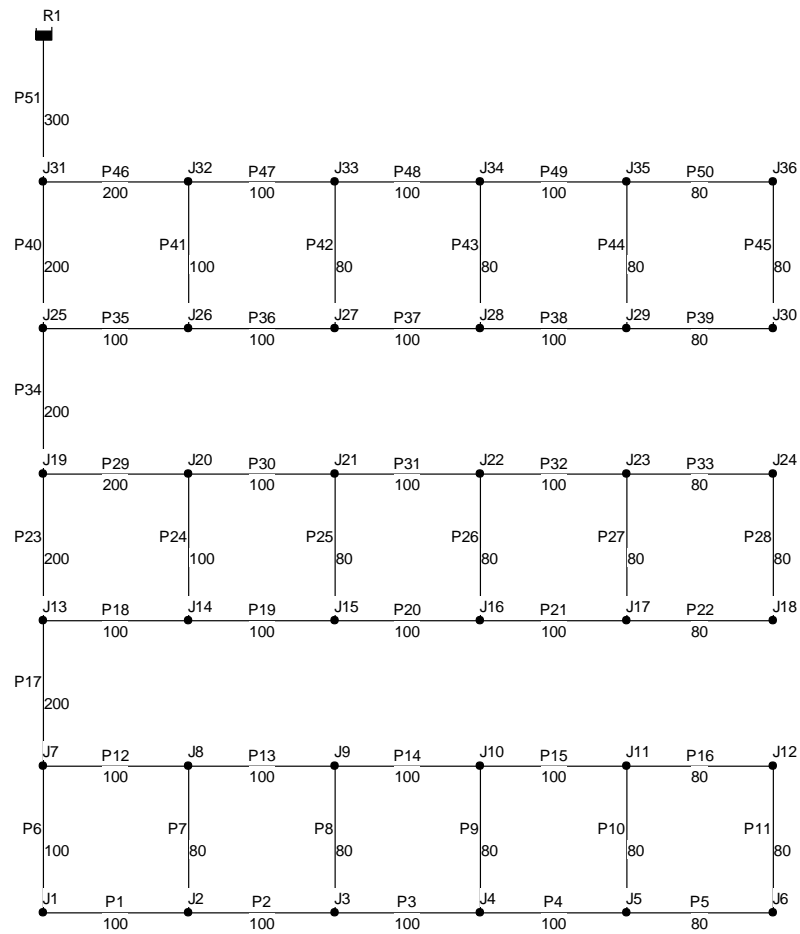


Figure 1. Hypothetical water distribution system.

### 3.1 Hydraulic Solution with EPANET

The hypothetical WDS was hydraulically simulated by means of the EPANET software. The results of EPANET simulation for pressures of nodes and flows of pipes are presented in Table 1. After EPANET simulation, pressure values at the nodes are in the limitations of the regulations. Minus sign of the flow means that its direction is counter clockwise in the loop.

Table 1. Node pressures and pipe flow and velocities after EPANET simulation

Node	Pressure (meters water)	Node	Pressure (meters water)	Pipe	Flow (l/s)	Velocity (m/s)	Pipe	Flow (l/s)	Velocity (m/s)
J1	38.00	J25	53.31	P1	7.76	0.99	P27	0.00	0.00
J2	33.23	J26	53.24	P2	7.60	0.97	P28	0.00	0.00
J3	28.65	J27	49.98	P3	5.97	0.76	P29	16.38	0.52
J4	25.71	J28	47.29	P4	4.00	0.51	P30	8.96	1.14
J5	24.32	J29	45.91	P5	2.00	0.40	P31	6.12	0.78
J6	23.17	J30	44.76	P6	-9.76	1.24	P32	4.00	0.51
J7	45.29	J31	58.60	P7	-1.84	0.37	P33	2.00	0.40
J8	34.22	J32	57.73	P8	-0.37	0.07	P34	-48.0	1.53
J9	28.70	J33	50.56	P9	-0.03	0.01	P35	0.81	0.10
J10	25.71	J34	47.32	P10	0.00	0.00	P36	6.32	0.81
J11	24.32	J35	45.91	P11	0.00	0.00	P37	5.70	0.73

Node	Pressure (meters water)	Node	Pressure (meters water)	Pipe	Flow (l/s)	Velocity (m/s)	Pipe	Flow (l/s)	Velocity (m/s)
J12	23.17	J36	44.76	P12	12.24	1.56	P38	3.98	0.51
J13	46.61			P13	8.40	1.07	P39	2.00	0.40
J14	45.45			P14	6.03	0.77	P40	-50.81	1.62
J15	41.47			P15	4.00	0.51	P41	-7.51	0.96
J16	38.62			P16	2.00	0.40	P42	-1.38	0.27
J17	37.22			P17	-24.00	0.76	P43	-0.28	0.06
J18	36.08			P18	3.62	0.46	P44	-0.02	0.00
J19	48.56			P19	7.04	0.90	P45	0.00	0.00
J20	47.91			P20	5.88	0.75	P46	19.19	0.61
J21	41.69			P21	4.00	0.51	P47	9.68	1.23
J22	38.62			P22	2.00	0.40	P48	6.30	0.80
J23	37.22			P23	-29.62	0.94	P49	4.02	0.51
J24	36.08			P24	-5.43	0.69	P50	2.00	0.40
				P25	-0.83	0.17	P51	72.0	1.02
				P26	-0.12	0.02			

### 3.2 MC Simulations with GIRAFFE

Seismic performance of the hypothetical WDS is evaluated using MC simulations in conjunction with GIRAFFE. Totally 52 MC runs were performed. RR for all pipes were taken as 2 repairs/km, pipe damage probability for ductile iron pipes was partitioned as 20% breaks and 80% leaks. Minimum pressure to elimination of a node is accepted as -5 psi (-0.34 Atm.). Duration of the simulation is taken as 0 hours because water source of the system is a reservoir not a tank, the amount of water will always be the same for the other simulation times. Pipe 51 is the only supply line of the system so it did not let be damaged.

Serviceabilities were calculated for each node and each simulation with the GIRAFFE. Serviceability of the system was calculated for each simulation by dividing the number of nodes whose request is meeting to the number of total nodes. Serviceability of the nodes was calculated by dividing the number of the simulations in which node demand is meeting to the total number of simulations. The means of the both serviceabilities should be the same and this is the general serviceability of the system. The general serviceability or the hypothetical WDS calculated as 0.601495. Serviceabilities for nodes and MC simulations are given in the Table 2.

Table 2. Serviceabilities of the nodes and MC simulations

Node	Serviceability	Node	Serviceability	MC Simulation	Serviceability	MC Simulation	Serviceability
J1	0.55769	J25	0.90385	MC1	0.77778	MC27	0.58333
J2	0.53846	J26	0.94231	MC2	0.75000	MC28	0.86111
J3	0.55769	J27	0.86538	MC3	0.44444	MC29	0.75000
J4	0.40385	J28	0.82692	MC4	0.86111	MC30	0.91667
J5	0.17308	J29	0.73077	MC5	0.55556	MC31	0.86111
J6	0.03846	J30	0.48077	MC6	0.75000	MC32	0.33333
J7	0.69231	J31	1.00000	MC7	0.86111	MC33	0.33333
J8	0.57692	J32	0.98077	MC8	0.47222	MC34	0.86111
J9	0.51923	J33	0.82692	MC9	0.83333	MC35	0.72222
J10	0.46154	J34	0.82692	MC10	0.16667	MC36	0.63889
J11	0.25000	J35	0.73077	MC11	0.61111	MC37	0.58333
J12	0.05769	J36	0.44231	MC12	0.63889	MC38	0.61111
J13	0.76923			MC13	0.30556	MC39	0.83333
J14	0.71154			MC14	0.69444	MC40	0.88889
J15	0.69231			MC15	0.75000	MC41	0.75000
J16	0.59615			MC16	0.69444	MC42	0.19444
J17	0.51923			MC17	0.83333	MC43	0.27778
J18	0.32692			MC18	0.88889	MC44	0.44444
J19	0.80769			MC19	0.52778	MC45	0.02778
J20	0.78846			MC20	0.83333	MC46	0.05556
J21	0.63462			MC21	0.30556	MC47	0.33333

Node	Serviceability	Node	Serviceability	MC Simulation	Serviceability	MC Simulation	Serviceability
J22	0.57692			MC22	0.91667	MC48	0.25000
J23	0.51923			MC23	0.83333	MC49	0.88889
J24	0.32692			MC24	0.19444	MC50	0.58333
				MC25	0.30556	MC51	0.33333
				MC26	0.58333	MC52	0.97222

### 3.3 Identification of Critical Links

Critical links of water supply systems are pipelines that significantly affect the system serviceability and reliability under earthquakes, and they correspond to relatively large UBI (Wang et al., 2010). In this study there are 36 junctions (nodes) and 51 pipes, so there should be 1836 DCI's and UBI's. As an example node 7 (J7) is evaluated with the pipes P6, P12, P17, P23, P34 and P40, UBI and DCI values are shown in Table 3. In this study when the demand (2 l/s) is satisfied for a node  $i$  than satisfaction of  $Q_i$  approved or counted. Pipe  $j$  is accepted as damaged when break or leak occurs in the pipe or when water cannot flow in the pipe although it is undamaged because of the negative pressure.

Table 3. Example UBI and DCI values

Node	Pipe	$m_1$	$n_1$	$m_2$	$n_2$	$m_3$	$n_3$	UBI	DCI
J7	P6	52	36	16	16	36	15	1.0	0.8957
J7	P12	52	36	12	12	40	24	1.0	0.3000
J7	P17	52	36	23	23	29	13	1.0	0.7930
J7	P23	52	36	16	15	36	21	0.7969	0.3542
J7	P34	52	36	20	19	32	18	0.6750	0.4218
J7	P40	52	36	30	26	22	10	0.5668	0.7728

### 3.4 Damaged Network Metrics With Igraph and QuACN

Igraph and QuACN are libraries of R software having functions about network metrics. In this study, average path length, diameter, density, betweenness and degree values were calculated by means of Igraph (Csardi and Nepusz, 2006) and spectral radius values were calculated by means of QuACN (Mueller et al., 2014). First of all network metrics were calculated for the undamaged hypothetical WDS. After each MC simulation if demand of a node cannot be satisfied then links (pipes) of this junction deleted from the network and metrics of the damaged network were calculated. Dissatisfaction of nodal demand may be caused by physical disconnection or presence of unsustainable negative pressures identified by the hydraulic network analyses. Network metrics of the undamaged hypothetical WDS and average network metrics of the damaged networks are given in the Table 4.

Table 4. Network metrics

	Average Path Length	Diameter	Density	Spectral Radius	Average Betweenness of Nodes	Average Degree of Nodes
Undamaged WDS	6.095238	15	0.07937	2.886731	89.1667	2.7778
Mean of all MC simulations of damaged WDSs	4.331949	10.2745	0.04556	2.733356	30.2334	1.5641

## 4. DISCUSSION AND CONCLUSIONS

When we examine the Table 2, serviceabilities of the nodes are varying between 0.03846 and 1.0, serviceability of the J31 is 1.0 because this node is the closest one to the reservoir. Similarly serviceability of J6 is the smallest because this node is the farthest one to the reservoir.

When we compare the UBI and DCI values of the node 7 according to the some pipes, UBI values with the neighboring pipes are 1.0 and UBI values are decreasing when the pipe being away from the J7. There is no a common comment for the DCI values with the neighboring pipes, for other pipes DCI values are increasing when the distance between the node and pipe is increasing.

After MC simulations all network metrics are decreasing comparing with the undamaged system's because of the connection loss of the network. There is a strong linear correlation between the Satisfied Demands and Graph Density as shown in the Figure 2.

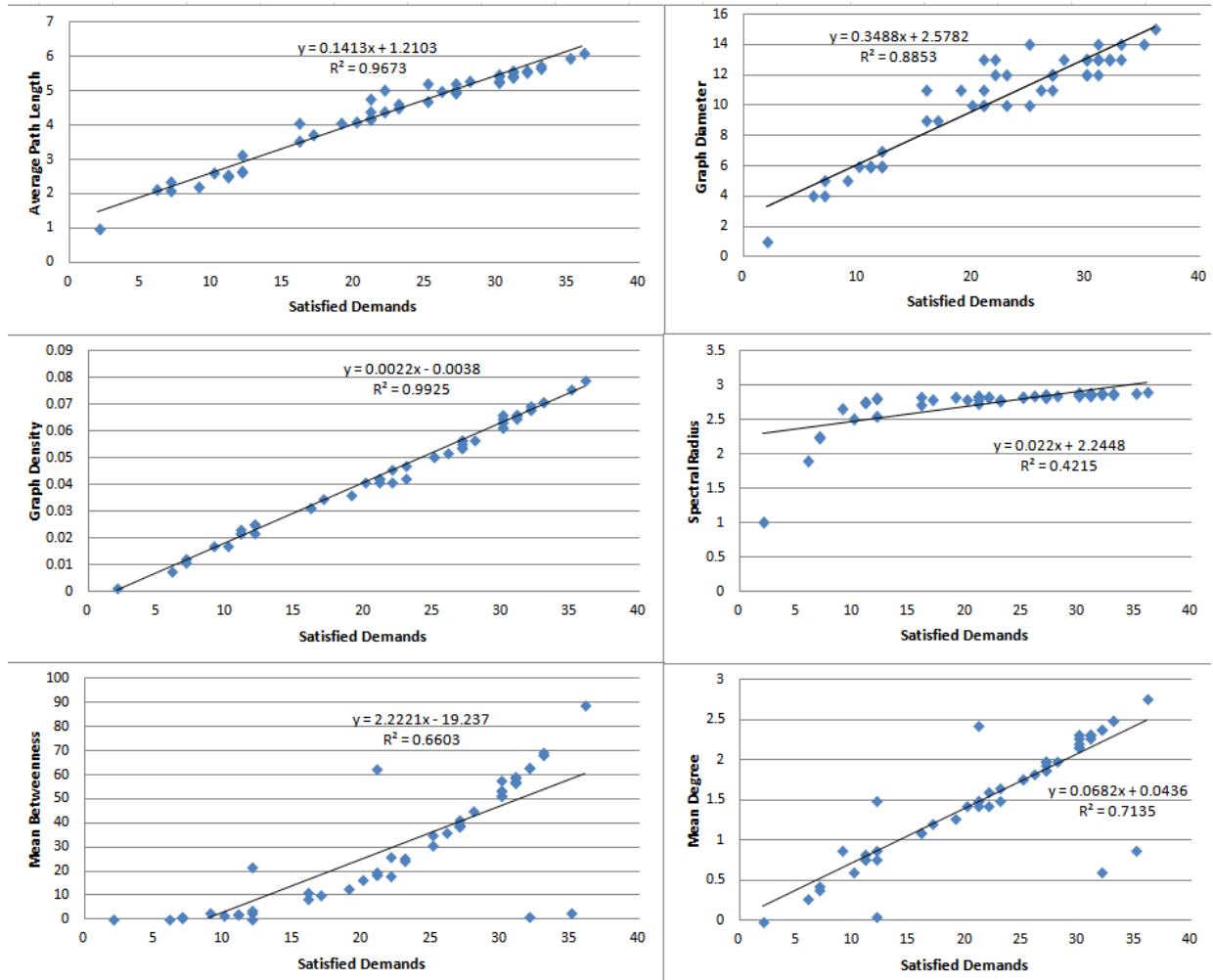


Figure 2. Satisfied demands vs. graph metrics.

## ACKNOWLEDGMENTS

The research reported in this paper was supported by Scientific and Technological Research Council of Turkey (TUBITAK) under Project No. 114M258. Partial grant provided by PAU BAP under Project No. 3019 to attend the conference is acknowledged.

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