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MONTE CARLO SIMULATION FOR URBAN WATER SUPPLY INFRASTRUCTURE AVAILABILITY

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ABSTRACT

The availability of a water distribution system is governed by the reliability of pipes in the distribution network and the components in the water supply pumping system. The failure pattern of such a system is difficult to understand due to the various inherent and external factors that have an impact on aging. This paper presents the application of 'Failure Modes and Effect Analysis' on an urban water distribution system in India to identify the potential failure modes of the system. Monte Carlo simulation model is used to estimate the availability of the system. The study revealed the deteriorating behaviour of this critical infrastructure and provides insight into the need for better maintenance strategies.

Keywords: water distribution system, availability, simulation.

1. INTRODUCTION

Water distribution system (WDS) is a complex infrastructure network consisting of pipes, junction joints, hydraulic devices and pumps used in delivering water to consumers in prescribed quantities and at desired pressure [5]. The various components in the water distribution infrastructure may fail frequently and hence reduce the availability of the system. Surveys carried out in different countries reveal that 35-60% of water is wasted in leakages in the pipelines [4]. Though significant research has been carried out in modelling the physical process of pipe deterioration and failure [1, 11, 15, 17] lack of pertinent data and highly variable environmental conditions pose severe challenges to these efforts. The lack of precise information about failure causes and pipeline conditions are the difficulties associated with proper pipeline maintenance [4]. Without identifying the potential failure modes which cause frequent water distribution system failures, it will not be possible to make a detailed and meaningful analysis of the performance of the system. And identifying the critical failure modes that contribute to WDS failure cannot be realized without a good methodology of modeling. Hence, there is a need to provide assistance in the form of predictive methodologies, which can forewarn the management with effective simulation models.

Monte Carlo simulation model can be used to investigate any complex system, failure patterns, and detailed aspects of component repair such as priorities and repair resource limitations. The operational states in which the system is found as a result of each failure or repair completion, are logged and used for determining a performance index of the system. Few researchers have used simulation methods for reliability assessment of water distribution networks [6, 12, 16]. This paper presents a simulation study of a real-life urban Water Distribution System (WDS) in India, in order to evaluate the performance of the water distribution system. The proposed simulation approach takes into account the random failure of multiple components in the pumping system as well as the water distribution pipe network. The remainder of the paper is organized as follows. A description of the water distribution system under study is given in Section 2. The failure study of the WDS is presented in Section 3. The Monte Carlo simulation model used in the performance assessment of the system is detailed in Section 4 while Section 5 provides a discussion of the results obtained.

2. WATER DISTRIBUTION SYSTEM UNDER STUDY

The modified urban water distribution system in India considered in the study is shown in Figure-1. The major components considered in the availability estimation of the water distribution system are the junction joints in the water distribution network, and the critical components in the water supply pumping system. All the pipes in the existing system are made of cast iron.

The water distribution pipe characteristics viz., the length and the diameter are shown in brackets. The failure time and repair time data considered in the study are taken from the published data [5, 7] and from the in-house records of the Water Supply and Sewerage Board for their own use.

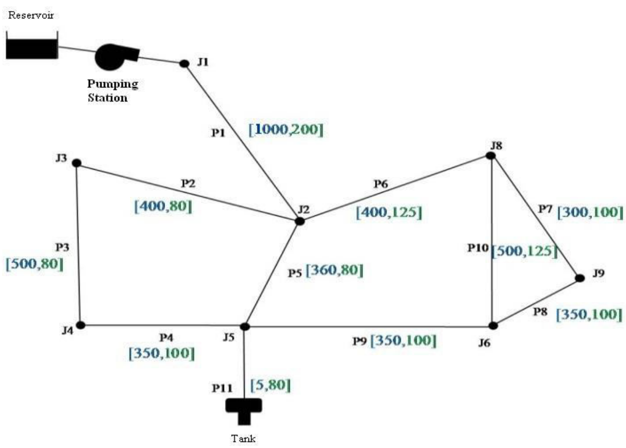

Figure-1. Schematic representation of water distribution system under study.

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3. FAILURE STUDY OF WATER DISTRIBUTION SYSTEM

The water distribution infrastructure availability depends on the failure-free components in the system. Pipe failure in the distribution network causes service disruption to the customers at or downstream of the failure location. The loss of discharge of water is also due to the fault in one or more pumping system components. Failure study of the pipe network and the pumping system components is carried out using 'Failure Modes and Effects Analysis' (FMEA) in order to facilitate the identification of potential components in the system that contribute to water infrastructure unavailability.

3.1 Ishikawa-fishbone diagram

A Cause-and-Effect Diagram also known as a Fishbone diagram proposed by Ishikawa, is a visualization tool used for identifying all the possible causes of a problem and in sorting ideas into useful categories [9]. The diagram identifies the most likely causes of the problem. The main causes of the water distribution system failure are determined after brainstorming with the water resources experts. And a Fishbone Diagram for the water distribution system failure is drawn to show both the primary and the secondary causes of the failure and for organizing the ideas generated from the brainstorming session. This technique is limited simply to reveal causes of effects, without considering the nature of these relationships. The cause and effect diagram for WDS failure is shown in Figure-2.

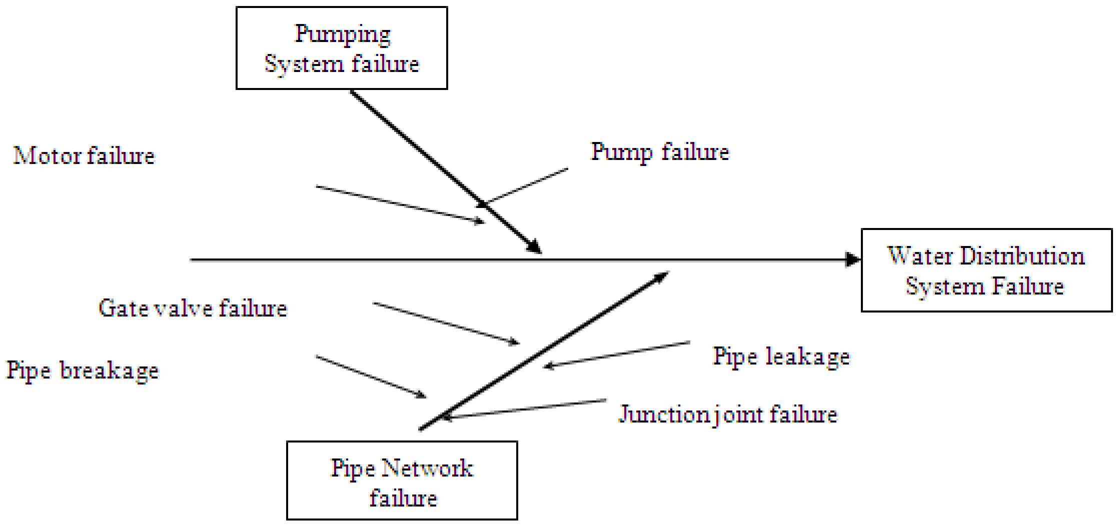

Figure-2. Fishbone diagram for failure of WDS under study.

3.2 Failure mode and effect analysis

A Failure Mode and Effect Analysis (FMEA) provide a framework for a detailed cause and effect analysis. FMEA is a step-by-step procedure for the systematic evaluation of the severity of the potential failure modes in a system [3]. The objective of employing FMEA in this study is to identify the potential failure modes in the water distribution system that should be given due consideration in the simulation model for availability estimation.

3.2.1 Risk prioritization

FMEA uses occurrence and detection probability criteria in conjunction with severity criteria to develop risk prioritization numbers for prioritization of failure modes. A Risk Priority Number (RPN) assessment is used to prioritize failure mode importance which is a function of three variables viz., frequency of occurrence of failure, severity of the failure effects at system level and detectability of the failure and it is computed as

RPN = Occurrence x Severity x Detectability

Occurrence is related according to failure probability, which represents the relative number of failures anticipated during the design life of the item. *Severity* is ranked according to the seriousness of the failure mode effect on the system. *Detectability* is an assessment of the ability of an inspection programme to identify a potential weakness before the component failure is recognized. The ranges of the values used to rank the frequency of the failure mode occurrence and the evaluation criteria used to rank the severity of the failure effects, the detectability of the failure modes are presented by Andrews and Moss [3].

The FMEA is carried out on the water distribution system under study. The various failure modes of the distribution pipe network and the water supply pumping system are obtained after brainstorming with the water resources experts and from the literature [7]. Table-1 shows the FMEA worksheet of the failure of the water distribution system. The worksheet consists of defining what can fail and the way it can fail and the effect of each failure mode on the water distribution system. The RPN is computed for each failure mode considered in the study.

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3.3 Pareto ranking

A Pareto chart is a graphical display of the 80-20 rule, for ranking the causes of problems from the most significant to the least significant [9]. Pareto analysis clearly separates 'the vital few from the trivial many' so that the trivial ones need not be considered for further analysis and it provides direction for possible improvement. This idea is applied to identify the potential failure components and events in the WDS under study.

The cumulative probabilities of occurrence of RPN values obtained for various failure modes of components/events are used to construct the Pareto chart. The Pareto chart constructed for the RPN values of the failure modes that cause WDS failure is shown in Figure-3. The cumulative frequency curve drawn on the histogram shows the relative magnitude of the failure events/modes.

Table-1. FMEA worksheet for WDS components/events.

ID	Description	Failure mode	Failure effect	Occurrence	Severity	Detectability	RPN
1	Rotor windings failure	Open/short circuit	Forced outage	3	8	7	168
2	Motor starter failure	Open circuit	Forced outage	1	6	6	36
3	Motor shaft failure	Crack/fracture	Forced outage	1	7	9	63
4	Motor Stator failure	Open/short Circuit	Forced outage	2	8	7	112
5	Pump bearing failure	Wear	Degraded performance	4	5	4	80
6	Impeller failure	Erosion/wear	Degraded performance	1	7	9	63
7	Gaskets worn-out	Wear	Degraded performance	4	2	4	32
8	Foot valve failure	Valve does not open/close	Discharge loss	3	8	4	76
9	Excess loading on pipe	Leakage	Discharge loss	1	6	6	36
10	Improper bedding under pipe	Leakage	Discharge loss	2	6	4	48
11	Corrosion pitting on pipe	Leakage	Discharge loss	1	5	6	30
12	Flow accelerated corrosion in pipe	Leakage	Discharge loss	1	1	2	2
13	Insufficient earth-cover over pipe	Crack	Discharge loss	3	4	5	60
14	Stress cracking in pipe	Crack	Discharge loss	1	3	5	15
15	Design flaws (pipe)	Crack	Discharge loss	1	6	5	30
16	Pipe damage due to miscreants	Breakage	Discharge loss	1	4	2	8
17	Pipe breakage during excavation of other works	Breakage	Discharge loss	3	8	3	72
18	Thermal fatigue in pipe	Crack in pipe	Discharge loss	1	4	6	24
19	Gate valve failure	Valve does not open/close	Uncontrolled water supply	1	5	6	30
20	Junction Joint failure	Leakage junction joint	Discharge loss	2	8	5	80

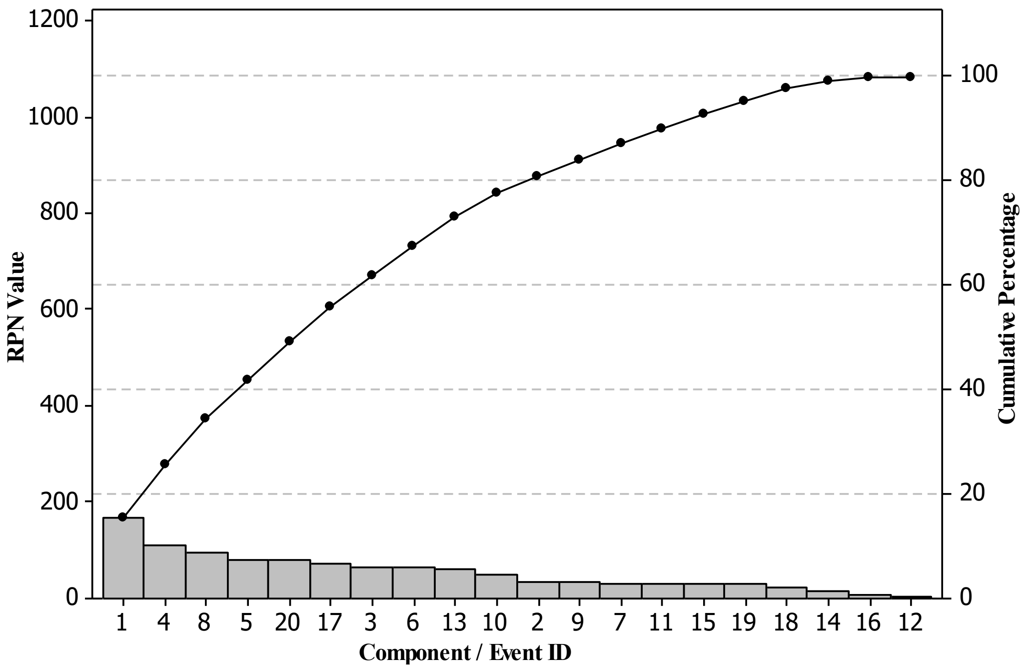

Figure-3. Critical components/failure modes Pareto Chart.

The potential water distribution pipe network failure modes identified from the study are insufficient earth-cover over pipe, Improper bedding under pipe, Junction joint failure, Excess loading on pipe and Pipe breakage during excavation of other works. The potential water pumping system failure events are Rotor windings failure Rotor windings failure, Motor starter failure, Foot valve failure, Pump bearing failure, Impeller failure, Motor shaft failure and Motor stator failure. These critical failure modes are considered in the availability evaluation of WDS.

4. WDS AVAILABILITY ASSESSMENT-THE SIMULATION MODEL

A computer simulation is an attempt to model a real-life or hypothetical situation on a computer so that it can be studied to see how the system works. Computer simulations have become a useful part of mathematical modeling of many engineering systems, to gain an insight into the operation of those systems. [13]. In this study Monte Carlo simulation of water distribution system is carried out to evaluate the performance of the system.

4.1 Failure and repair time data

The key parameters required for the availability assessment study are the failure rate and repair time. Accurate failure and repair data are required for a realistic system performance study. The data considered in the study are taken from the published data [2, 7, 5] and from the in-house records of the Metropolitan Water Supply and Sewerage Board for their own use.

The mean time to failure of pipes in the network which is a function of diameter and length of pipe is computed as [10],

$$\text{Breakage rate } b_{D_j} = \frac{16192.194}{D_j^{3.26}} + \frac{118.015}{D_j^{1.3131}} + \frac{183558.095}{D_j^{3.5792}} + 0.02615$$

$$\text{MTTF} = \frac{365}{L_j.\, b_{D_j}} \text{ days}$$

where Diameter D_j is in mm and Length L_j is in Km.

All the pipes are assumed to be in the useful life phase of the design life period, and so the failure rate of each pipe is computed as the reciprocal of the mean time to failure [8]. Table-2 shows the failure data of pipes in the water distribution system.

Table-2. Failure data of WDS pipes.

Pipe ID	Breakage rate, b_D (failures/Km/year)	Failure rate λ (failures/10^6 h)
P_1	0.140	15.987
P_2	0.439	20.032
P_3	0.439	25.040
P_4	0.323	12.900
P_5	0.439	18.029
P_6	0.242	11.071
P_7	0.323	11.057
P_8	0.323	12.900
P_9	0.323	12.900
P_{10}	0.242	13.838
P_{11}	0.439	0.2500

The failure rate for the different failure modes of the pipes are computed as discussed below: A weightage is

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assigned for each potential failure mode of the pipes in the distribution network as shown in Table-3.

Table-3. RPN ratios for the pipe failure modes.

Potential pipe failure mode	RPN value	RPN Ratio
Breakage during excavation of other works	72	0.33
Insufficient earth-cover over pipe	60	0.28
Improper bedding under pipe	48	0.22
Excess loading on pipe	36	0.17

The failure rate of a pipe due to a failure mode is computed by multiplying the RPN ratio of the corresponding failure mode of the pipe with the failure rate of the pipe. For example, the failure rate of pipe P_1 due to each failure mode is calculated as:

Failure rate of pipe P_1 due to breakage during excavation of other works
= 0.33 x 15.987 = 5.276 failures/10^6hr
Failure rate of pipe P_1 due to insufficient earth-cover over pipe
= 0.28 x 15.987 = 4.476 failures/10^6hr
Failure rate of pipe P_1 due to improper bedding under pipe
= 0.22 x 15.987 = 3.517 failures/10^6hr
Failure rate of pipe P_1 due to excess loading on pipe
= 0.17 x 15.987 = 2.718 failures/10^6hr
The Mean Time To Repair (MTTR) in hours, of a pipe j is calculated using the regression formula,
MTTR = $r.D_j^z$
where D_j is the pipe diameter in cm and the values of r and z are obtained using regression analysis.

The failure and repair time data of the various components in the water supply pumping system are collected from the in-house maintenance records and from the published data [5, 14]. Table-4 shows the failure and repair time data of the pumping components.

Table-4. Failure and repair time data of pumping components.

S. No.	Component	Failure rate (λ) per 10^6 hrs	Repair time (hrs)
1	Rotor windings	10	7
2	Motor Starter	30	3
3	Pump bearing	18	8
4	Impeller	4	12
5	Motor shaft	8	14
6	Motor stator	5	8
7	Foot valve	55	9
8	Junction joint	5	24

4.2 Assumptions

The following assumptions are made in the simulation study of water supply infrastructure system.

- One repair crew is continuously available and therefore waiting time to repair a pipe or any faulty pumping component is zero.
- Once a repair action begins on a component/pipe, it is fully completed without pre-emption.
- The times between failures follow exponential distribution.
- Repair times follow exponential distribution.

4.3. The simulation approach

It is assumed that the failure of any one component/event leads to the failure of the water distribution system. Therefore the WDS is assumed to have components that operate only in series.

The frequency of the unscheduled repair actions is a function of failure rates of the pipes in the distribution network and the components in the water pumping system. The total hours involved in these unscheduled repair actions is expressed as follows:

$$T_{ie} = \sum_{k=1}^{n} T_k$$

where
T_{ie} = total WDS 'ineffective utilization time' (in hours) during the planning horizon (i.e.25 years)
T_k =ineffective utilization time (in hours) of the water distribution system due to k^{th} unscheduled maintenance/repair.
n = number of unscheduled repairs during a 25 year period.

Hence the maximum possible Water supply infrastructure availability can be computed as

$$A = \frac{(T_d - T_{ie})}{T_d}$$

where T_d = total effective utilization time that the WDS is expected to function without failures (twenty five years, i.e. 2, 19, 000 hours).

This expression is a measure of the availability of the water distribution system because it gives the fraction of time the system is available for operation. The quality of service provided by a water supply infrastructure system is dependent on and can be directly related to the availability of this infrastructure and hence this measure is considered in the study.

4.4 Notations and terminology

λ	- Failure rate of a pipe or a pumping system component
MTTR	- Mean time to repair of a pipe or a pump component
T_{ie}	- Total ineffective utilization time of WDS
T_d	- Specified planning horizon (i.e. 25 years)
T_c	- Current clock time
E_s	- End simulation time
T_f	- Failure time of a component or a pipe
T_a	- Time of occurrence of a failure
T_r	- Repair time of a pipe or a component
T_{rc}	- Repair completion time
NMIE	- time of occurrence of the next imminent event
A	- Availability of water distribution system

4.5 Step-by-step procedure of simulation

Step 1: Set $T_c = T_{ie} = 0$.
Input E_s and T_d.
Input λ and *MTTR* of all pipes and pump components
Determine T_f of all pipes and pump components.
Step 2: $T_a = \min(T_f)$
$T_c = T_a$
Remove T_a from the set of failure times, (T_f)
Step 3: Make crew busy;
Determine T_r for failed pipe/component
Compute T_{rc}
Step 4: $NMIE = \min(T_{rc}, T_a, \text{Es})$
If $NMIE = T_{rc}$
then
{
$T_c = T_{rc}$
Update T_{ie}
Update λ and compute T_f of failed pipe/component
Return to Step 2;
}
else
if $(NMIE = E_s)$
then
{
Calculate and report WDS availability, *A*.
Stop.
}

4.6 Setting the run length of the simulation experiment

The run length for the simulation experiment is varied and the WDS availability is computed for each run length. The WDS availability values obtained for various run lengths are given in Table-5.

Table-5. WDS Availability value for various run lengths.

Run length	Water distribution infrastructure availability value			
	Replication 1	**Replication 2**	**Replication 3**	**Replication 4**
40	83.76	82.28	84.42	84.16
50	82.26	83.63	85.22	86.34
60	82.58	83.59	83.67	82.25
70	85.56	84.93	83.32	83.97
80	84.75	83.04	84.18	85.44
90	85.16	84.46	84.34	83.77
100	84.61	85.11	83.12	83.43

H_o: No significant difference in WDS availability value due to changes in run length.
H_1: Significant difference in WDS availability value due to changes in run length.

The ANOVA is conducted with the WDS availability values and the ANOVA for run length is given in Table-6.

Table-6. ANOVA for run length of simulation experiment.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F_{cal}
Run length	6.814236	6	1.1357	1.0104
Error	23.60418	21	1.1240	
Total	30.41841	27		

Since the value obtained for F_{cal} does not exceed 2.57, the value of $F_{0.05}$ with 6 and 21 degrees of freedom, the null hypothesis H_o is accepted at the 0.05 level of significance. Hence, the run length for simulation is fixed as 40. Initial ANOVA conducted with the availability values for less than 40 runs indicated that there is no significant difference in the availability values due to changes in run length.

5. RESULTS

Simulation is terminated after the simulation time reaches twenty five years as the proposed WDS design period is twenty five years. The simulation is replicated over a number of 40 runs and the availability of the WDS during its design period is estimated to be 0.8445. This means that that water distribution system with all its pumping system components and the pipe network has an infrastructure availability of 84.45%. Hence, there is a scope for improving the availability value of the water distribution infrastructure by implementing proper maintenance and rehabilitation strategies. The availability values of the water distribution system infrastructure obtained for different periods of its service are studied and the effect of the age of the system on the infrastructure availability of the system is shown in Figure-4.

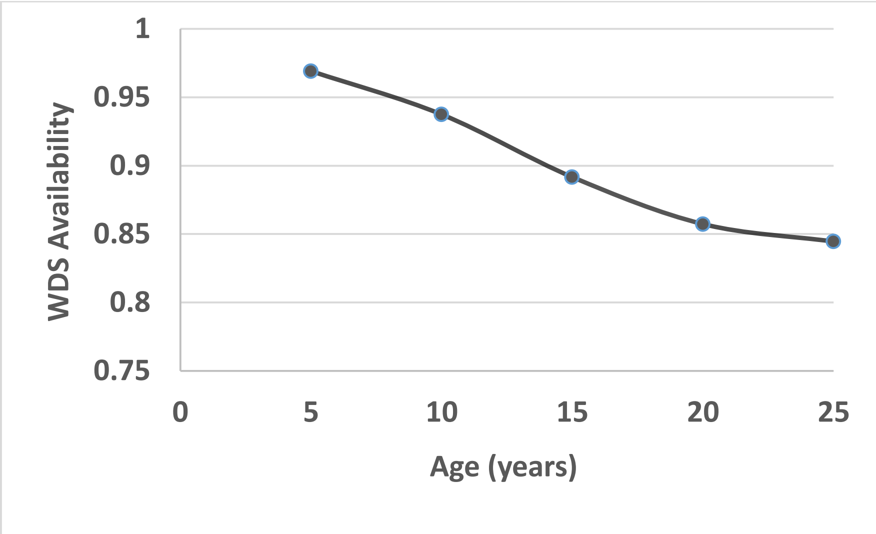

Figure-4. Effect of WDS age on system availability.

It is found that the system availability decreases as the age of the WDS increases. The uncertainty in the behavior of the mechanical components in the WDS such as pipes, junction joints, pump and motor has an impact on the availability of the system. It is also observed that the infrastructure availability of the system decreases fast after 10 years of service. This may be due to aging and the possible deterioration taking place in the WDS during its wear-out phase of its life.

6. SUMMARY

An urban water distribution system should be able to supply drinking water in required quantities to all consumers at their tapping points throughout the design period. The availability of such a system is governed mostly by the reliability of the pipes in the distribution network and also the water supply pumping system. The failure study of a real-life water distribution system requiring high levels of infrastructure availability for the supply of drinking water to the consumers is presented. The Failure modes and effects analysis (FMEA) is carried out to study the failure behaviour of the water distribution system. A simulation model is used to study the performance of the existing water distribution system. Various maintenance strategies can be employed on the WDS in order to maximize the infrastructure availability of the system.

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