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Pipe Failure Probabilities of Water Distribution Systems

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Abstract

In this paper, we will describe two methods so-called Poisson method and Generic Expectation Function (GEF) method for using to find pipe failure probabilities of water distribution systems which implicitly designed by engineers. In order to develop GEF method using means and coefficients of variation of input random variables through employing probability distribution such as normal distribution, is adopted. In this paper, 9 water distribution systems which are located in Terengganu, Malaysia and 1 hypothetical water distribution system, have been used for illustrating these mentioned both methods from which the comparison can be discussed. Besides that, hydraulic simulation software, EPANET has been applied to get the input variables for each project. Failure probability of each pipe is focused on failure probability of pipe to fulfil the demand denoted by P_A and also pipe replacement probability denoted by P_B.
Keywords: ***pipe failure probabilities, pipe replacement probability, Poisson method, Generic Expectation Function method***

1. INTRODUCTION

As known, water distribution systems are consist of pipes, valves, pumps, storage tanks, reservoirs and groundwater wells. Water distribution systems are important to provide all consumers with good water quality at all time in adequate amounts because water is one of the most important living needs. Distribution of water refers to the actual delivery of treated water to homes, businesses and industries. All pipes in the distribution system conveying water that ultimately leads to consumer's premises, are called main components (Sincero and Sincero, 1996).

The analysis of breaks in pipes of the network is essential step towards reliability evaluation (Maglionico and Ugarelli, 2002). Pipe failure's rate depends on many variables including the pipe material, size, construction practices, soil type and age (Shinstine et al., 2002). The failure rate of different pipes is determined by length of pipe for Poisson method, but for GEF method, four parameters are selected which are pipe roughness coefficients, nodal demand, tank and reservoir water level are determined to compute failure rate. These variables then used in normal distributions to get demand failure probability, P_A and pipe replacement probability, P_B. The importance of knowing pipe failure probability is because it can affect system's reliability which will be described in another paper.

As far as we know that only two papers have studied about GEF method. One is in (Al-Zahrani and Syed, 2004) in which the pipe failures probability has been determined for their hypothetical water distribution networks. The other is in (Tyagi and Haan, 2001) in which GEF method has been developed as a function of means and coefficient of variations of input random variables with different probability distribution by considering a power function and taking higher order moments of it about the origin. They used GEF method to calculate the risk which was defined as the probability of failure of a storm sewer system by calculating expectations of the input random variables.

In both (Goulter and Coals, 1986) and (Su et al., 1987), the probability of failure of individual pipes have been computed by using Poisson method.

Therefore, it can be said that no study has been attempted to clarify the actual water distribution systems that have been constructed so far. So, in this paper, pipe failure probabilities for 10 water distribution systems are discussed from which, 9 of them have been designed fully by professional engineers and one is hypothetical.

This paper is organised as follows. In Section 2, we discuss about why this paper is published and also, a flow chart of the methodology for our research, is given. The Poisson and Generic Expectation methods are described in sections 3 and 4 respectively. In sections 5 and 6, the calculation of P_A and P_B are being described, respectively, which constitute the complete pipe failure probability, P_{com}. Numerical results for 10 projects are shown in Section 7 where in this section, we also display example of the calculation of complete pipe failure probability, P_{com}. In Section 8, results of pipe failure probability using both methods are listed. Moreover, the comparisons of using both methods are discussed in Section 9 together with the conclusion.

2. PROBLEM STATEMENT

In any water distribution systems, pipe breakdown will occur any time even though the systems have been built by experienced engineers. We, as a consumer also experienced the situation when we have no water supply at our house. We never know how often that situation will happen. That's why; we can predict the breakdown by looking at the pipe failure probabilities. Due to the fact that the failure of water distribution systems causes serious consequences in the social and economical environment, these characteristics have become a field of observation. This paper is focused on pipe failure probabilities than other components such as valves, pumps, storage tanks and others in the system because we believe that pipes always become the main cause of system failure (Mays, 2004).

In Figure 1, we provide the brief chart about the Poisson and GEF methods which are implemented in our calculation. The view of the project 10 is given in Figure 2.

In Figure 2, it is shown that one tank is needed for above project to distribute water to consumer. P1 until P85 is number of each pipe in the project and J1 until J62 is the number of each junction. Also, the arrow shows direction of water for each pipe.

In this paper, two methods for computing the pipe failure probability, are considered where each one is described in the next two sections.

3. POISSON METHOD

The Poisson Method is utilized according what has been done in (Goulter and Coals,1986) and (Su et al., 1987) for computing the pipe failure probability by using the Poisson probability given by

$$P_i = 1 - e^{-\beta_i} \tag{3.1}$$

with

$$\beta_i = r_i L_i \tag{3.2}$$

where β_i is expected number of failures per year for pipe i, r_i is equal to expected number of failures per year per unit length of pipe i and L_i is the length of pipe i $(i = 1,\ldots,m)$ with m is the number of pipes in the system . The value of $r_i = 0.35742$ breaks per km per year is obtained from the data provided by Syarikat Air Terengganu Sdn Bhd (SATU, 2006). The breaks refer to pipe leakage or pipe damage because of construction either SATU projects or any other projects.

4. GENERIC EXPECTATION FUNCTION (GEF) METHOD

By using a power function

$$Y = X^r, (r \geq 0) \tag{4.1}$$

the $k-th$ order moment of Y about the origin can be obtained as

$$\mu_k^r = E[Y^k] = E[X^{kr}] = \int_{-\infty}^{\infty} X^{kr} p_x(x)dX \tag{4.2}$$

where $p_x(x)$ is the probability density function of X.

By assuming different probability density functions as developed and presented in (Tyagi, 2000), the expression for calculating higher order expectations for Triangular Distribution is

$$E\left[X^r\right] = \frac{\mu^r}{6(r+1)(r+2)CV^2}\left[\left(1+CV\sqrt{6}\right)^{r+2} + \left(1-CV\sqrt{6}\right)^{r+2} - 2\right], \tag{4.3}$$

for Exponential Distribution is

$$E\left[X^r\right] = \mu^r \Gamma(r+1), \tag{4.4}$$

and for Normal Distribution is

$$E\left[X^r\right] = \mu^r\left[1 + \frac{r(r-1)}{2}CV^2 + ... + \frac{r(r-1)(r-2).....(r-n+1)}{2^{n/2}(n/2)}CV^n + ...\right] \tag{4.5}$$

where μ is a mean of each pipe, CV is coefficient of variation which equals to standard deviation per mean, and r is as in (4.1).

5. PIPE FAILURE PROBABILITY, P_A

Calculation of failure probability, P_A of pipe to fulfil the demand is described as follows. Failure is assumed to occur when the flow in the pipe exceeds the capacity of the pipe regarding to (Al-Zahrani and Syed, 2004). According to Hazen-William equation (Viessman and Hammer, 2005), the flow rate in the pipe Q_p in International System of Unit (SI), is computed by

$$Q_p = 0.849 C_{HW} A R^{0.63} S^{0.54} \tag{5.1}$$

where C_{HW} is the Hazen-William coefficient, A is the pipe cross-sectional area in meter square, R is hydraulic radius equal to area /wetted perimeter in meter and S is the slope of hydraulic grade line and *S* equals to head loss (h) over length of pipe (L). There is no unit for *S* and all the calculation above is in SI unit.

Considered pipe is flowing full, then the cross-sectional area, $A = \pi d^2 / 4$ where d is the diameter of pipe, and for wetted perimeter, $P = \pi d$. After substituting the values of A and R in equation (5.1), we have

$$Q_p = 0.27842 C_{HW} d^{2.63} S^{0.54} \quad (5.2)$$

The flow rate directed into the pipe will be equal to pipe distribution factor multiplied by the demand at the junction (Al-Zahrani and Syed, 2004) is given by

$$Q_D = D_p Q_{J_i} \quad (5.3)$$

where D_p is a distribution factor of the pipe and Q_{J_i} is water demand at junction i (litre per second, lps). Therefore the performance function, Z_A of the pipe can be defined as

$$Z_A = Q_D - Q_p \quad (5.4)$$

In (Al-Zahrani and Syed, 2004), $Z_A = Q_p - Q_D$ which is different from (5.4) since we have found that the value of Q_D is bigger than Q_p except when there is no demand at the junction. By assuming the normal distribution, the equation (5.4) is used to find the failure probability, P_A of the pipe to fulfil the demand of the junction. EPANET Software is used for determining the distribution factor, D_p. Distribution factor of each pipe is calculated by dividing the flow rate in the pipe with water demand of the junction towards which water is flowing (Al-Zahrani and Syed, 2004).

6. PIPE REPLACEMENT PROBABILITY, P_B

In (Shamir and Howard, 1979), break rate equation is given by

$$N(t) = N(t_0)e^{G(t-t_0)} \quad (6.1)$$

where N(t) is the number of breaks per 1000 meter length pf pipe in year t where t is equal to time in years, t_0 is base year for the analysis and G is growth rate coefficient (1/year).
The threshold break rate Brk_{th} (Loganathan et al., 2002) gives the critical break rate for optimal replacement of the pipe and can be expressed as

$$Brk_{th} = \frac{\ln(1+R_d)F_n}{C_{n+1}} \quad (6.2)$$

where R_d is discount rate, F_n is replacement cost at time t_n and C_{n+1} is repair cost of $(n+1)-th$ break.

By combining the formulae given by equations (6.1) and (6.2), we have

$$Z_B = Brk_{th} - N(t) = \frac{\ln(1+R)F_n}{C_{n+1}} - N(t_0)e^{G(t-t_0)} \tag{6.3}$$

from which the pipe replacement probability, P_B can be determined, assuming Z_B follows the normal distribution. Finally the complete failure probability, P_{com} can be calculated by

$$P_{com} = P_A \times P_B. \tag{6.4}$$

7. NUMERICAL TESTING

In this paper, 10 projects including 9 projects supplied by (SATU, 2006) which had been fully designed by professional engineers and 1 hypothetical project, have been used to obtain the values of the probability of the pipe failures of each of the pipe for each project.

In the following, we provide an example for computing the complete pipe failure probability using GEF for pipe number 1 in Figure 2, as illustration.

Example 7.1 (Calculation of complete pipe failure probability for Pipe 1)

To calculate P_{com}, all pipes are considered individually and the complete pipe failure probability of each pipe is calculated. Consider pipe 1 and junction 2 as shown in Figure 2. In order to calculate the failure probability P_A of the pipe to fulfil the demand, the input parameters of equations (5.3) and (5.4) are determined only for the population of its own project that means without using any random sample. This will make sure the accurateness for the value of the pipe failure probability that we obtained. Different from (Al-Zahrani and Syed, 2004), they picked random values to get the input parameters for their projects.

The probability distributions are assumed for the input variables and their means and coefficient of variations are calculated as shown in Table 7.1. According to the assumed probability distributions, higher order expectations are calculated (Tyagi, 2000) as shown in Table 7.2. Using these higher order expectations, distributional characteristics are calculated as shown in Table 7.3.

1. Calculation of demand failure probability P_A

For S, there are two values for CV because the value for first one is used at 1+CV which we got from project itself and one more is assumption to get CV for S in range between 0.002 and 0.003 when at the calculation of 1-CV for all the pipes for all projects. This assumption is regarding to the discussion with SATU officer, (Yunus, 2006).

Assuming normal distribution for Z_A, the probability of failure P_A is determined as follows

$$P_A = P(Z < 0)$$

$$= P\left(Z < \frac{X - \mu_{Z_A}}{\sigma_{Z_A}}\right) = P\left(Z < \frac{0 - 0.030346}{0.0727823}\right)$$

$$= P(Z < -0.416945)$$

$$= 0.3372 .$$

2. Pipe replacement probability P_B

Assuming normal distribution for Z_B, the probability of failure P_B is determined as follows

$$P_B = P(Z < 0)$$

$$= P\left(Z < \frac{X - \mu_{Z_B}}{\sigma_{Z_B}} \right) = P\left(Z < \frac{0 - 0.513322}{0.552729} \right)$$

$$= P(Z < -0.92870466)$$

$$= 0.1762 .$$

Therefore, complete failure probability, P_{com} is given by

$$P_{com} = P_A \times P_B = 0.3372 \times 0.1762 = 0.05941. \blacklozenge$$

Example 7.2 (Calculation of complete pipe failure probability for Pipe 2)

Assuming normal distribution for Z_A, the probability of failure P_A is determined as follows

$$P_A = P(Z < 0)$$

$$= P\left(z < \frac{X - \mu_{Z_A}}{\sigma_{Z_A}} \right) = P\left(Z < \frac{0 - 0.135307}{0.205311} \right)$$

$$= P(Z < -0.6590343)$$

$$= 0.2546 .$$

2. Pipe replacement probability P_B

Assuming normal distribution for Z_B, the probability of failure P_B is determined as follows

$$P_B = P(Z < 0)$$

$$= P\left(z < \frac{X - \mu_{Z_B}}{\sigma_{Z_B}} \right) = P\left(Z < \frac{0 - 1.53997}{1.65819} \right)$$

$$= P(Z < -0.928705)$$

$$= 0.1762 .$$

Therefore, complete failure probability, P_{com} is given by

$$P_{com} = P_A \times P_B = 0.2546 \times 0.1762 = 0.0449. \blacklozenge$$

8. RESULTS

Regarding to the Table 8.1, P1 until P9 is refer to each project respectively. The number of pipes for each project refers to the number of the ending of the data for example the number of pipes for project 1 (P1) is 15. All the pipe failure probabilities value shows are calculated using Poisson method while in Table 8.2, the pipe failure probabilities value shows are calculated using Generic Expectation method.

In Table 8.2, 10 projects are listed including one project is for hypothetical project. This hypothetical project show that any reasonable component such as tank (see Figure 3), the value of pipe failure probability does not affect. This hypothetical project is adopted from Project 9.

Data that have been obtained by using Poisson method for actual water distribution system shown that the value for pipes failure probabilities for Project 1 until Project 9 is very different from one pipe to another. For example, for Project 1, the value for pipe failure probability is 0.0053 while for pipe 2 is 0.0453. But, the value for pipes failure probabilities by using GEF method for all nine projects looks slightly the same for each pipe. For example, for Project 1, the value for pipe failure probability is 0.0259 while for pipe 2 is 0.0255. The difference between these two values using Poisson method is 0.0400 while using GEF method is 0.0004.

Table 8.3 and 8.4 contains the result for hypothetical water distribution system with different elevation to observe either the failure probabilities for each pipes will affected by elevation using each method. For Table 8.3 no elevation is mentioned because for Poisson method only length of each pipes are needed to get the failure probability. The highest failure probability is 0.0799 and the lowest is 0.0034. In Table 8.4, the results show the failure probabilities of each pipe with different elevation for each node using GEF method. It shows that the failure probability for each pipe is not affected by elevation from our observation. The highest failure probability is 0.0734 and the lowest is 0.0640.

9. DISCUSSION

From Poisson method we can see that Project 1 until 9, the difference of pipe failure probability for each pipe is bigger than GEF method. Highest differentiation using Poisson method is 0.1370 while using GEF method is 0.0322. This result obviously shows that using GEF method is more efficient than Poisson method. This is because system will fail involved many factors such as flow rate directed to the pipe exceeding water capacity in the pipe. In GEF method this factor is taken as one of the data to get pipe failure probability. GEF method is focused on the changes that happened in water distribution system in details meanwhile Poisson method only focused on the length of each pipe.

The same situation happened that we can observe in hypothetical water distribution system, using both methods. This differentiation of using both methods are observed because of Poisson method only required the expected number of failures per year of pipe and length as parameter, so, the shorter the length, the smaller the value of pipe failure probability. As for GEF method, many parameters are required to get the failure rate such as pipe roughness, pipe diameters, number of breaks in the pipe, repair and replacement costs of pipe. So, we can conclude that by using GEF method is more accurate compare with Poisson method.

Meanwhile, results of pipe failure probability for hypothetical project shows that the failure for each pipe in that project is the biggest value among any other projects with mean pipe failure value is 0.065. This mean, all the projects that had been designed fully by engineers are good quality of designs. For different elevation of each pipe in hypothetical water distribution system shows that the failure value is not affected by elevation and for modification of Project 9 with additional tank, the results for pipe failure probability of each pipe is almost the same without modification.

10. CONCLUSION

We can conclude that pipe failure probability using GEF method involved the changes that happened in water distribution system such as flow rate in the pipe. Pipe failure probability using GEF method is alike for each project and for Poisson method pipe failure probability is different for each pipe because it is only refer to the length of each pipe. We also conclude that the genuine designs that we studied in this paper are good quality design.

Any comparison between this paper and (Al-Zahrani and Syed, 2004) cannot be discussed because we had found there is a few mistakes in that paper at page 84, which is the value for their D_p is more than 1 and the value of order of expectations for Q_D and Q_P that we found the units in their calculation are not the same.

(Al-Zahrani and Syed, 2004) mentioned only hypothetical water distribution system, but in our paper we discussed about hypothetical and genuine design and we observed that the actual design is better in sense of pipe failure probability because of the failure is smaller than hypothetical design.

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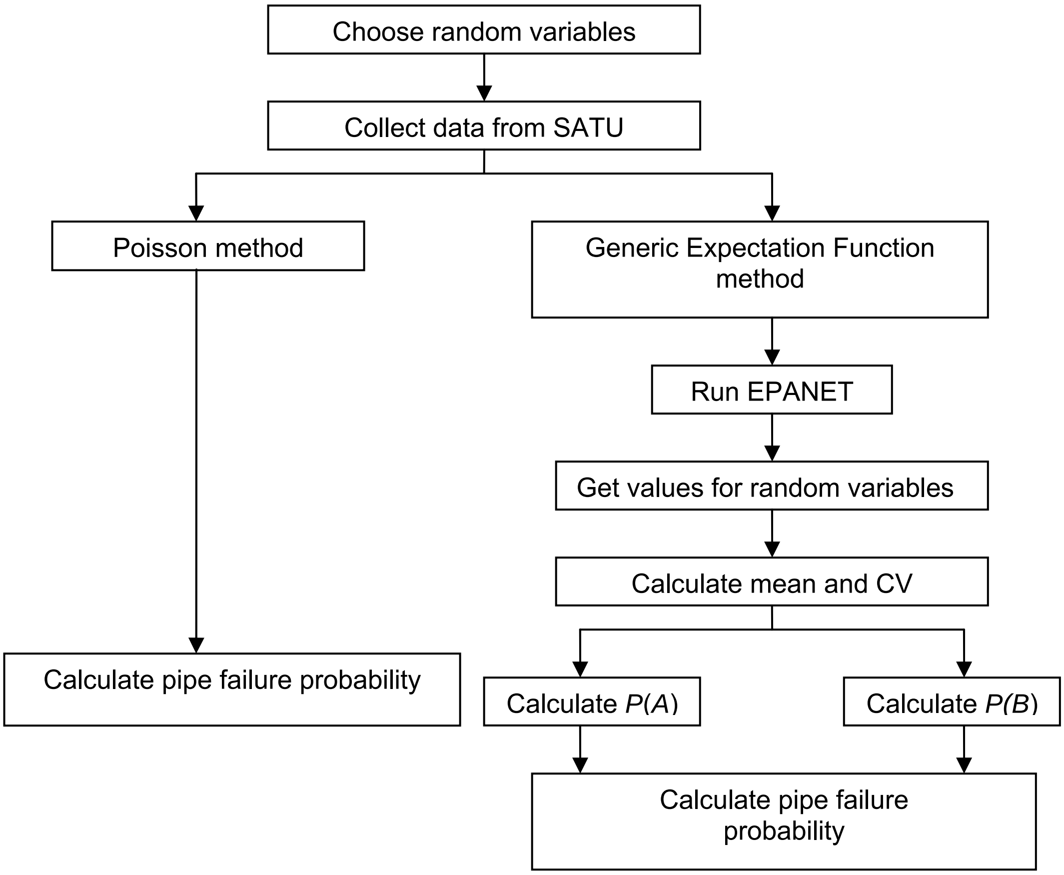

Figure 1. Flow chart of the methodology

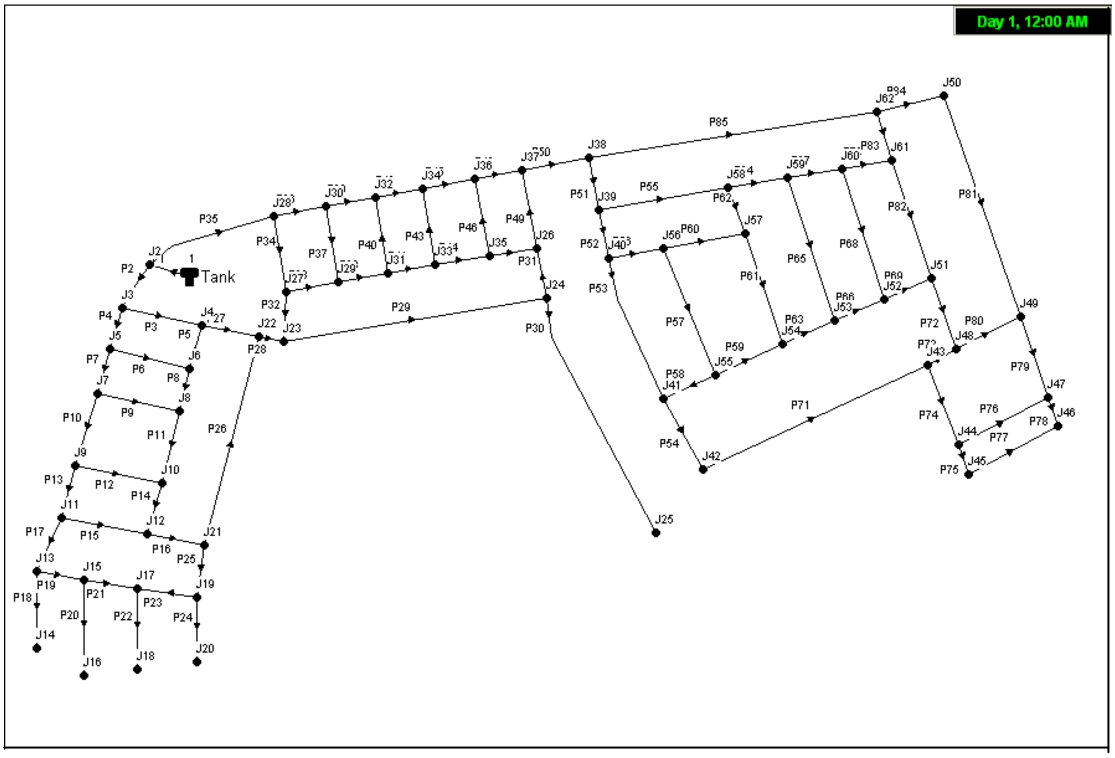

Figure 2 : Water distribution system for Project 9

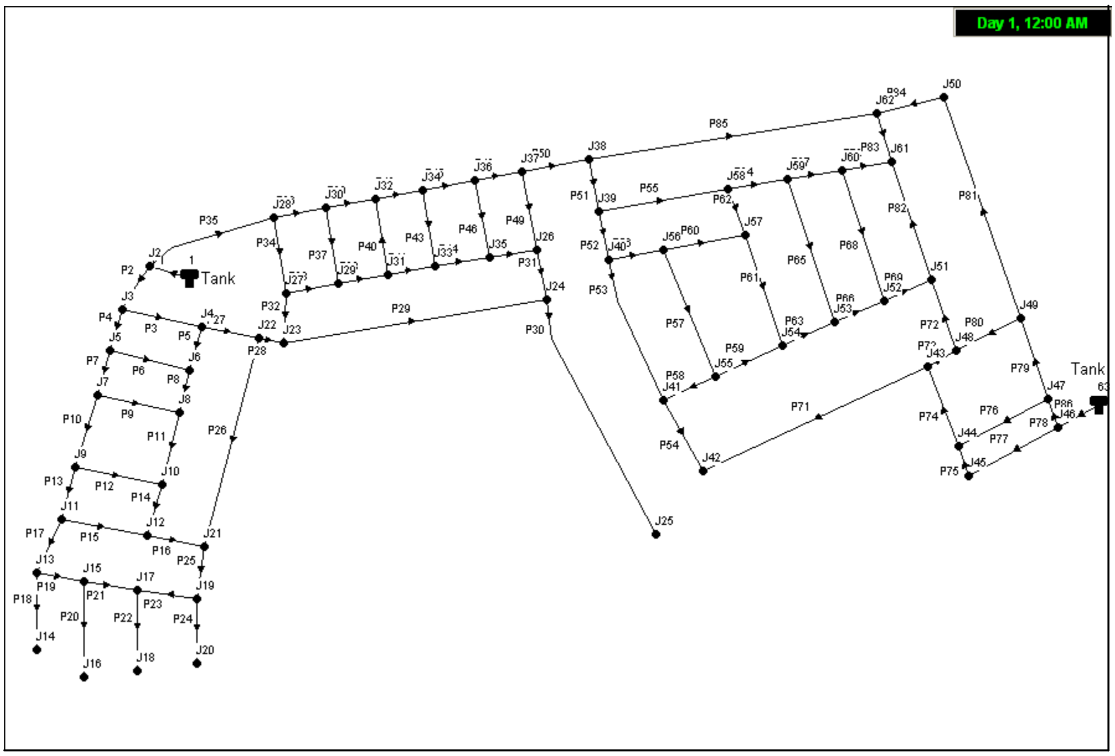

Figure 3 : Water distribution system for Project 9 with additional tank

Table 7.1 : Statistics of input variables

Input Variable	Mean (μ)		Coefficient of Variation, CV		Distribution
	Pipe 1	Pipe 2	Pipe 1	Pipe 2	
C_{HW}	100	100	0	0	Normal
D(m)	0.250	0.250	0.192737	0.192737	Triangular
S	0.00287	0.00052	1.38431 / 0.196566	1.38431 / 0.196566	Triangular
D_p	1.00	0.3983	0.48823	0.48823	Normal
Q_{J_i} (lps)	0.00	0.37	1.13338	1.13338	Normal

Table 7.2 : Order of expectations

	K=1		K=2		K=3		K=4	
	Pipe 1	Pipe 2	Pipe 1	Pipe 2	Pipe 1	Pipe 2	Pipe 1	Pipe 2
$E[C_{HW}^K]$	100	100	10000	10000	1e+006	1e+006	1e+008	1e+008
$E[d^{2.63K}]$	0.02817	0.02817	0.00098	0.00098	3.97e-005	3.97e-005	1.79e-006	1.79e-006
$E[S^{0.54K}]$	0.03869	0.01538	0.00228	0.00036	0.000147	9.21e-006	1.00e-005	2.50e-007
$E[D_p^K]$	1	0.39830	1.23837	0.196459	1.90082	0.1201	3.34352	0.08415
$E[QJ^K]$	0	0.37000	0	0.312755	0	0.36353	0	0.43013
$E[Q_D^K]$	0	0.14737	0	0.061443	0	0.04366	0	0.03619
$E[Q_p^K]$	0.03035	0.01206	0.00622	0.00098	0.00162	0.00010	0.00050	1.25e-005
$E[Z_A^K]$	0.03035	0.13531	0.00622	0.060461	0.00162	0.043561	0.00050	0.03618

Table 7.3 : Distributional characteristics (Demand failure probability)

Output Variables	Mean		Variance		Standard Deviation		Coefficient of Variation	
Simbol	μ		σ^2		σ		CV	
	Pipe 1	Pipe 2	Pipe 1	Pipe 2	Pipe 1	Pipe 2	Pipe 1	Pipe 2
Q_D	0	0.147371	0	0.039725	0	0.199312	0	1.352450
Q_p	0.030346	0.012064	0.005297	8.3718e-04	0.072782	0.028934	2.3984	2.398400
Z_A	0.030346	0.135307	0.005297	0.042152	0.072782	0.205311	2.3984	1.517370

Table 7.4 : Statistics of input variables

Input Variable	Mean		Distribution
	Pipe 1	Pipe 2	
$N(t_0)$	0.005355	0.016065	Exponential
G	0.051	0.051	Exponential
R_d	0.06	0.06	Exponential
F_n	1425	4275	Exponential
C_{n+1}	160	160	Exponential

Table 7.5 : Order of expectations

	K=1		K=2		K=3		K=4	
	Pipe 1	**Pipe 2**	**Pipe 1**	**Pipe 2**	**Pipe 1**	**Pipe 2**	**Pipe 1**	**Pipe 2**
$E[N(t_0^K)]$	0.005355	0.016065	5.735e-005	0.000516	9.214e-007	2.487e-005	1.974e-008	1.599e-006
$E[G^K]$	0.051	0.051	0.005202	0.005202	0.000796	0.000796	0.000162	0.000162
$E[R_d^K]$	0.06	0.06	0.0072	0.0072	0.001296	0.001296	0.000311	0.000311
$E[F_n^K]$	1425	4275	4.061e+006	3.655e+007	1.736e+010	4.688e+011	9.896e+013	8.016e+015
$E[C_{n+1}^K]$	160	160	51200	51200	2.457e+007	2.458e+007	1.573e+010	1.572e+010
$E[N(t)^K]$	0.005635	0.016906	5.765e-005	0.000518	9.221e-007	2.490e-005	1.974e-008	1.599e-006
$E[Bth^K]$	0.518957	1.55687	0.569067	5.1216	0.914973	24.7043	1.95672	158.494
$E[Z_B^K]$	0.513322	1.53997	0.569009	5.12108	0.914972	24.7043	1.95672	158.494

Table 7.6 : Distributional characteristics

Output Variable	**Mean**		**Variance**		**Standard Deviation**		**Coefficient of Variation**	
Symbol	μ		σ^2		σ		CV	
	Pipe 1	Pipe 2	Pipe 1	Pipe 2	Pipe 1	Pipe 2	Pipe 1	Pipe 2
N(t)	0.005635	0.016906	0.000026	2.330e-04	0.005089	0.015266	0.903039	0.903039
Bth	0.518957	1.55687	0.299751	2.697741	0.547495	1.642480	1.054990	1.054990
Z_B	0.513322	1.53997	0.305509	2.749594	0.552729	1.658190	1.076770	1.076770

Table 8.1: Pipe failure probabilities for each projects using Poisson Method

Pipe	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**
1	0.0053	0.0076	0.0689	0.0046	0.0229	0.0075	0.0082	0.1423	0.0053
2	0.0453	0.0022	0.0389	0.0385	0.0327	0.0036	0.0385	0.0212	0.0159
3	0.0247	0.0530	0.0194	0.0170	0.0399	0.0156	0.0282	0.0386	0.0402
4	0.0212	0.0146	0.0337	0.0170	0.0159	0.0212	0.0282	0.0142	0.0177
5	0.0117	0.0108	0.0399	0.0399	0.0191	0.0288	0.0222	0.0159	0.0177
6	0.0398	0.0499	0.0351	0.0117	0.0488	0.0121	0.0014	0.0316	0.0402
7	0.0186	0.0509	0.0351	0.0205	0.0173	0.0226	0.0278	0.0124	0.0177
8	0.0177	0.0038	0.0198	0.0282	0.0166	0.0212	0.0288	0.0177	0.0177
9	0.0447	0.0566	0.0198	0.0194	0.0212	0.0977	0.0453	0.0194	0.0402
10	0.0191	0.0332	0.0229	0.0177	0.0261	0.0114	0.0180	0.0488	0.0351
11	0.0463	0.0076	0.0177	0.0261	0.0460	0.0089	0.0285	0.0316	0.0351
12	0.0358	0.0162	0.0292	0.0194	0.0222	0.0152	0.0278	0.0385	0.0402
13	0.0163	0.0162	0.0552	0.0107	0.0436	0.0107	0.0180	0.0488	0.0177
14	0.0330	0.0065	0.0194	0.0440	0.0191	0.0152	0.0316	0.0089	0.0177
15	0.0335	0.0274	0.0222	0.0184	0.0184	0.0078	0.0229	0.0177	0.0402
16		0.0183	0.0278	0.0392	0.0759	0.0229	0.0247	0.0351	0.0177
17		0.0135	0.0364	0.0313	0.0250	0.0268	0.0282	0.0212	0.0177
18		0.0038	0.0364	0.0194	0.0565	0.0416	0.0309	0.0351	0.0282
19		0.0065	0.0229	0.0224	0.0198	0.0191	0.0205	0.0212	0.0177
20			0.0395	0.0159	0.0626	0.0145	0.0320	0.0351	0.0282
21				0.0526	0.0313	0.0071	0.0402	0.0504	0.0194
22				0.0149	0.0477	0.0145	0.0205	0.0316	0.0282
23				0.0316	0.0208	0.0271	0.0316	0.0471	0.0229
24				0.0201	0.0170	0.0268	0.0247	0.0471	0.0229
25					0.0222	0.0226	0.0285	0.0177	0.0177
26					0.0187	0.0082	0.0306	0.0177	0.0854
27					0.0198	0.0107	0.0264	0.0589	0.0177
28					0.0652	0.0149	0.0333	0.0351	0.0053
29						0.0135	0.0099	0.0264	0.0870
30						0.0145	0.0201	0.0177	0.0788

Pipe	P1	P2	P3	P4	P5	P6	P7	P8	P9
31						0.0061	0.0194	0.0264	0.0177
32							0.0099	0.0282	0.0177
33							0.0170	0.0299	0.0149
34							0.0275	0.0454	0.0312
35							0.0061	0.0419	0.0521
36							0.0572	0.0194	0.0194
37							0.0368	0.0089	0.0316
38							0.0447	0.0247	0.0194
39							0.0299	0.0247	0.0194
40							0.0211	0.0177	0.0316
41								0.0297	0.0194
42								0.0589	0.0194
43								0.0177	0.0316
44								0.0212	0.0194
45								0.0368	0.0194
46								0.0177	0.0316
47								0.0368	0.0194
48								0.0142	0.0194
49								0.0368	0.0316
50								0.0247	0.0282
51								0.0053	0.0194
52								0.0124	0.0212
53								0.0316	0.0504
54								0.0089	0.0212
55								0.0159	0.0471
56								0.0247	0.0194
57								0.0177	0.0419
58								0.0089	0.0212
59								0.0639	0.0316
60								0.0159	0.0351
61								0.0177	0.0316
62								0.0488	0.0212
63								0.0351	0.0212
64								0.0247	0.0229
65								0.0453	0.0453
66								0.0177	0.0212
67								0.0177	0.0247
68								0.0316	0.0385
69								0.0159	0.0212
70								0.0385	0.0247
71								0.0229	0.1000
72								0.0419	0.0212
73								0.0385	0.0071
74								0.0281	0.0316
75								0.0247	0.0089
76								0.0177	0.0316
77								0.0316	0.0316
78									0.0089
79									0.0316
80									0.0198
81									0.0672
82									0.0316
83									0.0194
84									0.0212
85									0.1048

Table 8.2 : Pipe failure probabilities for each projects using Generic Expectation Method

Pipe	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
1	0.0259	0.0556	0.0137	0.0057	0.0315	0.0581	0.0620	0.0601	0.0594	0.0607
2	0.0255	0.0243	0.0148	0.0054	0.0315	0.0581	0.0405	0.0601	0.0449	0.0438
3	0.0255	0.0239	0.0137	0.0057	0.0301	0.0348	0.0410	0.0421	0.0594	0.0421
4	0.0247	0.0235	0.0135	0.0041	0.0301	0.0339	0.0394	0.0384	0.0594	0.0607
5	0.0259	0.0556	0.0132	0.0041	0.0301	0.0581	0.0394	0.0601	0.0415	0.0410
6	0.0255	0.0239	0.0132	0.0050	0.0292	0.0348	0.0389	0.0601	0.0410	0.0415
7	0.0251	0.0235	0.0135	0.0058	0.0288	0.0339	0.0384	0.0601	0.0483	0.0472
8	0.0251	0.0239	0.0132	0.0051	0.0620	0.0339	0.0620	0.0415	0.0410	0.0410
9	0.0255	0.0243	0.0140	0.0046	0.0292	0.0581	0.0389	0.0601	0.0410	0.0415
10	0.0247	0.0556	0.0135	0.0047	0.0292	0.0343	0.0620	0.0384	0.0594	0.0607
11	0.0255	0.0556	0.0130	0.0040	0.0310	0.0581	0.0620	0.0384	0.0410	0.0410
12	0.0247	0.0556	0.0132	0.0039	0.0288	0.0339	0.0389	0.0384	0.0410	0.0415
13	0.0247	0.0239	0.0130	0.0037	0.0288	0.0581	0.0394	0.0384	0.0410	0.0410
14	0.0251	0.0235	0.0132	0.0040	0.0292	0.0339	0.0399	0.0384	0.0406	0.0410
15	0.0263	0.0235	0.0130	0.0043	0.0288	0.0339	0.0394	0.0449	0.0406	0.0410
16		0.0235	0.0135	0.0048	0.0288	0.0581	0.0620	0.0432	0.0410	0.0410
17		0.0243	0.0130	0.0046	0.0292	0.0000	0.0389	0.0394	0.0594	0.0607
18		0.0235	0.0130	0.0038	0.0288	0.0581	0.0384	0.0389	0.0406	0.0410
19		0.0556	0.0130	0.0038	0.0288	0.0343	0.0620	0.0389	0.0594	0.0607
20			0.0135	0.0037	0.0288	0.0581	0.0389	0.0389	0.0406	0.0410
21				0.0038	0.0292	0.0339	0.0389	0.0389	0.0594	0.0607
22				0.0039	0.0288	0.0339	0.0620	0.0394	0.0406	0.0410
23				0.0039	0.0292	0.0581	0.0389	0.0389	0.0406	0.0410
24				0.0042	0.0297	0.0339	0.0394	0.0389	0.0406	0.0410
25					0.0301	0.0339	0.0389	0.0601	0.0406	0.0410
26					0.0301	0.0581	0.0389	0.0394	0.0406	0.0410
27					0.0292	0.0339	0.0384	0.0384	0.0415	0.0415
28					0.0292	0.0581	0.0405	0.0384	0.0406	0.0410
29						0.0339	0.0620	0.0601	0.0410	0.0410
30						0.0339	0.0384	0.0389	0.0406	0.0410
31						0.0000	0.0394	0.0389	0.0410	0.0410
32							0.0399	0.0601	0.0415	0.0415
33							0.0620	0.0384	0.0410	0.0410
34							0.0384	0.0384	0.0443	0.0432
35							0.0620	0.0384	0.0594	0.0607
36							0.0620	0.0389	0.0426	0.0421
37							0.0620	0.0389	0.0421	0.0421
38							0.0384	0.0601	0.0421	0.0415
39							0.0399	0.0601	0.0421	0.0421
40							0.0620	0.0394	0.0410	0.0415
41								0.0384	0.0415	0.0410
42								0.0394	0.0421	0.0415
43								0.0601	0.0410	0.0415
44								0.0601	0.0410	0.0410
45								0.0416	0.0420	0.0415
46								0.0389	0.0410	0.0415
47								0.0389	0.0406	0.0410
48								0.0389	0.0432	0.0421
49								0.0389	0.0406	0.0410
50								0.0389	0.0594	0.0607
51								0.0601	0.0594	0.0607
52								0.0601	0.0594	0.0607
53								0.0601	0.0472	0.0426

Pipe	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
54								0.0384	0.0406	0.0410
55								0.0384	0.0507	0.0438
56								0.0384	0.0472	0.0426
57								0.0384	0.0443	0.0415
58								0.0384	0.0426	0.0415
59								0.0389	0.0426	0.0415
60								0.0389	0.0443	0.0415
61								0.0389	0.0438	0.0415
62								0.0384	0.0426	0.0449
63								0.0384	0.0438	0.0415
64								0.0601	0.0594	0.0607
65								0.0389	0.0449	0.0421
66								0.0394	0.0449	0.0415
67								0.0601	0.0594	0.0607
68								0.0601	0.0443	0.0415
69								0.0601	0.0406	0.0410
70								0.0384	0.0406	0.0410
71								0.0384	0.0406	0.0410
72								0.0389	0.0406	0.0410
73								0.0384	0.0406	0.0410
74								0.0384	0.0594	0.0607
75								0.0389	0.0594	0.0607
76								0.0384	0.0406	0.0410
77								0.0384	0.0406	0.0421
78									0.0406	0.0421
79									0.0406	0.0410
80									0.0406	0.0410
81									0.0594	0.0607
82									0.0406	0.0410
83									0.0406	0.0410
84									0.0594	0.0607
85									0.0410	0.0410
86										0.0421

Table 8.3: Pipe failure probabilities using Poisson method

Poisson Method							
Pipe	**Failure**	**Pipe**	**Failure**	**Pipe**	**Failure**	**Pipe**	**Failure**
1	0.0075	19	0.0205	37	0.0224	55	0.0148
2	0.0082	20	0.0658	38	0.0637	56	0.0210
3	0.0508	21	0.0659	39	0.0288	57	0.0256
4	0.0287	22	0.0228	40	0.0204	58	0.0208
5	0.0034	23	0.0205	41	0.0651	59	0.0256
6	0.0204	24	0.0657	42	0.0204	60	0.0214
7	0.0543	25	0.0205	43	0.0204	61	0.0256
8	0.0101	26	0.0760	44	0.0648	62	0.0205
9	0.0204	27	0.0230	45	0.0205	63	0.0233
10	0.0510	28	0.0205	46	0.0216	64	0.0215
11	0.0287	29	0.0657	47	0.0799	65	0.0233
12	0.0205	30	0.0202	48	0.0651	66	0.0220
13	0.0658	31	0.0432	49	0.0217	67	0.0245
14	0.0205	32	0.0461	50	0.0215	68	0.0194
15	0.0450	33	0.0220	51	0.0213	69	0.0208
16	0.0234	34	0.0206	52	0.0179	70	0.0262
17	0.0561	35	0.0655	53	0.0323	71	0.0204
18	0.0205	36	0.0206	54	0.0215		

Table 8.4: Pipe failure probabilities using GEF method

Pipe	GEF Method			Pipe	GEF Method		
	Elevation (1)	Elevation (2)	Failure		Elevation (1)	Elevation (2)	Failure
1	57	5.2	0.0633	37	51	5.2	0.0653
2	57	5.2	0.0673	38	47	5.2	0.0646
3	58.5	5.2	0.0653	39	47	5.2	0.0646
4	58.75	5.2	0.0646	40	53	5.2	0.0640
5	59	5.2	0.0646	41	51.5	5.2	0.0640
6	59.5	5.2	0.0734	42	52	5.2	0.0640
7	58	5.2	0.0646	43	52	5.2	0.0640
8	58	5.2	0.0653	44	51	5.2	0.0640
9	58	5.2	0.0646	45	51.5	5.2	0.0640
10	58.75	5.2	0.0646	46	49.5	5.2	0.0653
11	57.5	5.2	0.0646	47	45	5.2	0.0640
12	57.5	5.2	0.0646	48	43	5.2	0.0653
13	56.5	5.2	0.0653	49	48.5	5.2	0.0640
14	56.5	5.2	0.0660	50	48	5.2	0.0694
15	53	5.2	0.0680	51	47	5.2	0.0640
16	51	5.2	0.0646	52	45.5	5.2	0.0640
17	56.5	5.2	0.0653	53	44	5.2	0.0640
18	56	5.2	0.0653	54	43	5.2	0.0640
19	57	5.2	0.0646	55	42	5.2	0.0646
20	56	5.2	0.0646	56	42	5.2	0.0646
21	52	5.2	0.0653	57	46	5.2	0.0640
22	51	5.2	0.0653	58	46	5.2	0.0640
23	56	5.2	0.0646	59	47	5.2	0.0640
24	54	5.2	0.0640	60	44.5	5.2	0.0640
25	54	5.2	0.0640	61	45.5	5.2	0.0640
26	50	5.2	0.0646	62	44.5	5.2	0.0640
27	50	5.2	0.0646	63	44	5.2	0.0640
28	55.5	5.2	0.0646	64	44	5.2	0.0640
29	52.5	5.2	0.0646	65	43	5.2	0.0640
30	54	5.2	0.0640	66	43.5	5.2	0.0640
31	51.5	5.2	0.0653	67	43.5	5.2	0.0640
32	50	5.2	0.0646	68	40	5.2	0.0646
33	50	5.2	0.0646	69	39.5	5.2	0.0640
34	54	5.2	0.0646	70	39.5	5.2	0.0640
35	52	5.2	0.0640	71	39.5	5.2	0.0646
36	52.5	5.2	0.0646				