Environment Protection Engineering

Vol. 29 2003 No. 2

HALINA HOTLOŚ*

RELIABILITY LEVEL OF MUNICIPAL WATER-PIPE NETWORKS

Methods for assessing the required reliability level of water-supply systems (WSS) are presented. Analysis of reliability level is carried out for two municipal water-pipe networks (Brzeg and Opole) which have been investigated previously. Failure indices and average duration of failure are established. Making use of these parameters, the availability factors for the two water-pipe networks are calculated and compared with the reliability level values postulated by other investigators.

The furtherance of comprehensive investigations of water-supply systems, which are in service now, as well as a thorough analysis of the available literature in order to establish the desired reliability level for the WSS has taken on a sense of urgency, because the postulated values are confusing.

NOTATIONS

WSS – water-supply system,
K – reliability level (availability factor),
K_r – required reliability level,
f_f – frequency (number) of failure,
T_f – duration of failure,
I – number of inhabitants,
Q – quantity of the water delivered,
Q_n – total water demand,
$Q_{\lim}$ – limit quantity of the water delivered,
Q_p – production capacity,
SbWDe – subsystem of water delivery,
SbWDis – subsystem of water distribution,
T_s – average time of serviceability,
T_{rp} – average time of repair preparation,
T_{dr} – average duration of damage removal,
λ – average failure rate,
Δt – time interval,
L – length of pipeline,

* Wrocław University of Technology, Institute of Environment Protection Engineering, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland.

μ – repair rate,
H_{max} – maximum pressure,
ΔH – daily pressure variations.

1. INTRODUCTION

The design, management and modernization of water-supply systems (WSS) involve not only technological and economical considerations, but also reliability analysis. However, owing to the increasing complexity of the continuous modernized or rehabilitated WSSs (and this includes their time- and space-related productivity), their reliability is difficult to assess. Random failures of any WSS element may also affect water supply to the users. Temporal cut-offs or episodes of low-quality water supply are likely to encompass the entire WSS, be felt only locally or pass unnoticed by the users.

The reliability of WSSs is analyzed using reliability determination or reliability compliance tests carried out in the course of service. The data needed for the assessment of the reliability indices can be found primarily in the reports on the repair, overhauls, periodical surveys, etc., of the pipeline in service or in the reports and documentation collected by the waterworks.

The objective of reliability tests for particular elements of the WSS is to identify the damage-contributing factors and to take appropriate measures for their elimination, as well as to establish how the functioning of a given element affects the reliability of the entire system.

To describe the reliability level of the WSS use is made of a number of indices. Of these, the availability factor K, which describes the probability that the system will function appropriately, has found the widest acceptance. The value of K is established primarily on the basis of the failure rate and failure duration, since these two parameters are of paramount importance in terms of the users' needs.

As far as water-supply systems are concerned, the reliability theory can be applied in a variety of ways [1]–[3]. In engineering, however, the best one (in methodological terms) consists in determining the required reliability level for the whole K_r(WSS) system and in anticipating an improvement of the factor K at the stage of design, service or modernization so that the availability factor of the K(WSS) system reached the desired level. According to the definition presented in [3], the factor K_r(WSS) shows the level at which the services provided by the WSS satisfy the user's needs, and temporary discontinuities in rendering such services or temporary deterioration of service quality occur seldom.

2. DETERMINATION OF K_r(WSS)

The value K_r(WSS) is very difficult to establish, as this requires a thorough analysis of the WSS performance and structure as well as of the capital and running costs involved, to say nothing of the losses resulting from random failure. One of the available methods of determining the level K_r(WSS) includes observations of failures, the resulting water loss, health implications, etc., as well as utilization of past experience [3]. The values K_r, which have been determined in this way (following the assumption of the admissible frequency (f_f) and duration of failure (T_f) as well as the failure-related effects) on the basis of the results reported by some Soviet investigators, are listed in table 1 [1]. The proposed values of the reliability level refer to particular categories of waterworks; they involve the number of inhabitants (I) and the quantity (Q) of the water delivered related to the total water demand (Q_n).

Table 1

Required reliability levels, K_r(WSS) [1]

Category of WSS reliability	Users	Quantity of water supply; Q	f_f 1/year	T_f day	K_r(WSS)
I	Industrial plants where cut-offs in water supply cause serious damage	$Q = Q_n$	Additional reliability analysis is required		
		$Q_{\lim} \le Q < Q_n$			
		$Q < Q_{\lim}$			
II	Urban and industrial agglomerations, cities of $I > 500000$ ($Q_{\lim} = 0.35Q_n$)	$Q = Q_n$	–	–	0.9827329
		$0.7Q_n \le Q < Q_n$	3	2	0.9991713
		$Q_{\lim} \le Q < 0.7Q_n$	0.4	0.75	0.9999932
III	Towns of $50000 < I \le 500000$ ($Q_{\lim} = 0.3Q_n$)	$Q = Q_n$	–	–	0.9740959
		$0.7Q_n \le Q < Q_n$	3	3	0.9987534
		$Q_{\lim} \le Q < 0.7Q_n$	0.6	0.75	0.9999863
IV	Towns and settlements of $1000 < I \le 50000$ ($Q_{\lim} = 0.25Q_n$)	$Q = Q_n$	–	–	0.9150137
		$0.7Q_n \le Q < Q_n$	3	10	0.9972055
		$Q_{\lim} \le Q < 0.7Q_n$	1	1	0.9999452
V	Settlements of $I \le 1000$ ($Q_{\lim} = 0.2Q_n$)	$Q = Q_n$	–	–	0.8706849
		$0.7Q_n \le Q < Q_n$	3	15	0.9939726
		$Q_{\lim} \le Q < 0.7Q_n$	2	1	0.9994521

Three types of water supply have been distinguished [1]:

- providing total (100%) coverage of water demand ($Q = Q_n$),
- yielding coverage of water demand equal to, or greater than 70% ($Q \ge 0.7Q_n$),
- ensuring coverage lower than 70% ($Q_{\lim} \le Q < 0.7Q_n$).

The values of the parameters gathered in table 1 show that large WSSs require a higher K_r value compared to small WSSs. Higher reliability levels are also required when the water quantity delivered decreases with respect to the quantity demanded.

Making use of the same assumptions, other investigators [4] have proposed the reliability indices required for WSSs, which have been grouped into three categories (table 2). The criterion for the adoption of the values f_f, T_f and K_r also included the demands made on the reliability of water supply to particular households. It has been assumed, for example, that with large WSS (Category I) the average duration of cut-off in water supply must not be longer than 24 h a year at a frequency not greater than

- three times a year, with no 100% coverage of water demand,
- twice a year, with a decrease in the coverage of water demand to 70%,
- once in a 50-year period, with total cut-off in water supply to the users.

Table 2

Postulated reliability indices for WSSs [4]

Category of WSS reliability	Users	Quantity of water supply; Q	f_f 1/year	T_f day	K_r(WSS)
I	WSS serving $I > 50000$	$Q \approx Q_n$	3	24	0.9917809
		$Q \geq 0.7Q_n$	2	24	0.9945206
		$Q > 0$	0.02	24	0.9999453
II	WSS serving $500 < I \leq 50000$	$Q \approx Q_n$	6	24	0.9835617
		$Q \geq 0.7Q_n$	3	24	0.9917809
		$Q > 0$	0.2	24	0.9994542
III	WSS serving $I \leq 500$	$Q \approx Q_n$	12	24	0.9671233
		$Q \geq 0.7Q_n$	6	24	0.9835617
		$Q > 0$	1	24	0.9972603

The value K_r(WSS) can also be determined by including relevant economic parameters. And this requires the knowledge of the expenditures that are needed to establish the required reliability level as well as sufficient information on the costs involved when the system is prone to failure. So far, the method has not found acceptance, mainly because it is difficult to assess the cost of an unreliable system. What can be reliably assessed is the cost of damage repair [5] and the cost of water loss due to leakage [6]. Yet, there are some other economic effects and implications that are difficult to define unequivocally but cannot be neglected, namely those of a long-term consumption of low-quality water, to say nothing of the resulting discomfort experienced by the users.

3. RELIABILITY LEVEL OF THE WATER DISTRIBUTION SYSTEM

The WSS consists of two major subsystems: the subsystem of water delivery (SbWDe), which includes water intakes, water treatment plants, pumping stations, and transit pipes, and the subsystem of water distribution (SbWDis), which comprises water-pipe networks, pump houses, and surge shafts.

If K_r of the entire WSS is known, we can establish K_r of the two subsystems and of their components. The calculating methods described in the literature [1]–[3] have been developed by assuming an in-series reliability structure of the main WSS components. The methods proposed apply to balanced systems (where the production capacity Q_p and the rated capacity Q_n are approximately equal), to systems with excessive productivity (where $Q_p > Q_n$) as well as to systems with different coverage of water demand ($Q \approx Q_n$ or $Q < Q_n$). The calculating methods recommended in [3] are based on the assumption that the reliability of the SbWDe and the reliability of the SbWDis are equivalent. Hence,

$$K_r(\text{SbWDe}) = K_r(\text{SbWDis}). \tag{1}$$

The required reliability level of the water distribution system then takes the from

$$K_r(\text{SbWDis}) = \sqrt{K_r(\text{WSS})}\,. \tag{2}$$

4. ANALYSIS OF THE RELIABILITY LEVEL FOR THE WATER-PIPE NETWORKS OF CHOICE

The SbWDis consists of a network of delivery and distribution pipes as well as of a number of feeding objects (pumping stations, surge shafts). Being the last link in the generalized in-series WSS reliability structure, which supplies water directly to the user, the SbWDis contributes noticeably to the reliability of the entire WSS.

Experience shows that the reliability level of the SbWDis is strongly affected by the reliability level of the water-pipe network, because most of the failure is detected in pipes and in plumbing fittings. Pumping stations and surge shafts display a high reliability level.

The reliability level of water-pipe networks was analyzed on the basis of the data sets obtained during many years' service of two water supply systems.

The measure of the reliability level adopted for the water-pipe network was the availability factor K described as

$$K = T_s/(T_s + T_f), \tag{3}$$

or

$$K = 1/(1 + \lambda L T_f). \tag{4}$$

The average time of serviceability T_s (in days) between failures was calculated in terms of

$$T_s = 1/f_f, \tag{5}$$

where f_f denotes the number of failures in the time span of 24 h. The average duration of failure T_f (days or years) includes the time of repair preparation T_{rp} and the time of damage removal T_{dr}. Hence, we have

$$T_f = T_{rp} + T_{dr}\,. \tag{6}$$

The average failure rate λ (failure/km·a) was calculated as follows:

$$\lambda = f_f / \Delta t L, \tag{7}$$

where f_f denotes the number of failures in the time interval Δt (years), and L stands for the length of the pipeline (km).

Calculations were also carried out to establish the repair rate μ which describes the number of sequential repairs of the average T_f carried out during a year:

$$\mu = 1 / T_f . \tag{8}$$

4.1. CHARACTERIZATION OF THE WATER-PIPE NETWORKS BEING INVESTIGATED

The water-pipe networks of two municipalities, Brzeg and Opole (serving a population of about 40000 and 131000 inhabitants by the end of 2000, respectively), were analyzed for reliability level. The analysis included the failure rates for the main and distributing pipes, no consideration being given to plumbing fittings, which accounted for approximately 10% of the total number of failures and in most instances did not disturb water supply.

By the end of 2000, the Brzeg network had a length of 74.6 km, and a pipe diameter varied from 80 to 500 mm. Grey cast-iron pipes accounted for nearly 66% and PVC or PEHD pipes for 33% of the total network length. About 13% of the pipeline length were laid before 1940.

In the time span of 1991–2000, one-kilometer length of the network served about 530 inhabitants. There was a considerable drop in water consumption with all groups of users. This brought about a decrease in the network load factor l_n which describes the average daily volume of water pumped into the network per unit length (excluding plumbing fixtures). Thus, the value of l_n of the Brzeg water-pipe network decreased by 48% (from 250 $m^3/d{\cdot}km$ in 1991 to 129 $m^3/d{\cdot}km$ in 2000) and the length of the network increased by about 10% in the same time span.

Reliability factors were determined each year from 1991 to 2000 and in two investigated periods of service (Period I and Period II), i.e., before and after limitation of excess pressure in the network, and following a reduction in daily variations of pipe pressure. Thus, Period I (1991–August 1996) was characterized by H_{max} of 0.50 MPa, which decreased to 0.45 MPa in Period II (September 1996–2000) after the modernization of the pump house. Daily pressure variations were also reduced (from ΔH = 0.12 MPa to ΔH = 0.09 MPa). This accounted for a considerable reduction in failure rate and in water loss due to leakage [6]–[8].

The water-pipe network of Opole had a length of about 271 km (by the end of 2001) and a pipe diameter ranging from 80 to 1000 mm. Like in Brzeg, grey cast-iron pipes prevailed (covering about 57% of the total length, PVC or PEHD pipes accounting for approximately 35%). The proportion of the pipeline length laid before 1940 was 28% (excluding plumbing fixtures) [9].

In the time span investigated, about 480 inhabitants were served by the network of one-kilometer length. In the course of network reliability tests (i.e., between 1996–2001), the load factor l_n decreased by about 33% (from approximately 160 m^3/d·km in 1996 to 108 m^3/d·km in 2001) and the total length of the water-pipe network increased by about 8%.

4.2. ANALYSIS OF FAILURE RATE

Pipe failure is produced by a variety of factors which affect the pipeline in different ways, and their contribution varies from one WSS to another. As it may be inferred from our previous studies [5]–[8], three major factors should be blamed for the increase in the failure rate: the pipe material, the time of pipeline construction, and the pressure head in the pipes.

The water-pipe networks of Brzeg and Opole are characterized by a relatively low failure rate compared to those observed in other municipal WSSs of Poland.

In Brzeg, where two periods of pipeline service were distinguished according to the pressure head in the pipes (measured before and after modernization of the pump house), the average failure rate λ decreased from 0.30 failure/km · a in Period I to 0.21 failure/km · a in Period II (table 3). The modernization of the pumping station brought about a reduction in the maximum pressure (H_{max}) and in the daily pressure variations (ΔH) in the pipes.

Table 3

Reliability indices of the water-pipe network in Brzeg

Year/period of observation	f_f failure/a	L km	λ failure/km·a	T_s d	T_f h	T_f d	μ 1/a	K
1991	20	67.132	0.30	18.25	9.4	0.3917	932	0.978990
1992	19	68.909	0.27	19.26	5.7	0.2375	1541	0.987819
1993	18	71.511	0.25	20.28	6.6	0.2750	1327	0.986621
1994	23	73.106	0.31	15.87	6.3	0.2625	1390	0.983728
1995	26	73.873	0.35	14.04	7.8	0.3250	1123	0.977375
1996	27	74.426	0.36	13.56	8.2	0.3417	1071	0.975423
1997	13	74.426	0.17	28.08	6.2	0.2583	1413	0.990885
1998	18	74.426	0.24	20.28	5.9	0.2458	1485	0.988025
1999	11	74.426	0.15	33.18	6.4	0.2667	1369	0.992026
2000	16	74.581	0.21	22.81	6.0	0.2500	1464	0.989159
Period I (1991–Aug. 1996)	21.7	72.608	0.30	16.81	7.5	0.3125	1168	0.981749
Period II (Sept. 1996–2000)	15.7	74.480	0.21	23.25	6.2	0.2583	1413	0.989011

In Opole, the average failure rate established in the time span of 1996–2001 was slightly lower than in Brzeg, amounting to 0.14 failure/km · a (table 4). Since no information on the pressure head in the pipeline from this period is available, it was impossible to assess the contribution of this parameter to the occurrence of failure.

Table 4

Reliability indices of the water-pipe network in Opole

Year of observation	c failure/a	L km	λ failure/km·a	T_s d	T_f h	T_f d	μ 1/a	K
1996	43	250.184	0.17	8.51	31.4	1.3083	280	0.866746
1997	53	257.281	0.21	6.89	22.5	0.9375	389	0.880230
1998	23	261.227	0.09	15.87	18.2	0.7583	481	0.954397
1999	30	266.360	0.11	12.17	34.9	1.4542	251	0.893263
2000	42	269.671	0.15	8.71	15.3	0.6375	574	0.931800
2001	37	270.853	0.14	9.86	13.7	0.5708	639	0.945277
Average 1996–2001	38	262.611	0.14	9.60	22.6	0.9417	388	0.910672

The highest failure rate was determined with grey cast-iron pipes, which are prevalent in both water-pipe networks investigated (accounting for approximately 60% of the total length). In Brzeg, the average failure rate for cast-iron pipes totalled 0.38 failure/km·a and 0.23 failure/km·a in Period I and Period II, respectively; in Opole, the failure rate averaged 0.22 failure/km · a.

The failure rate established with plastic pipes (PVC, PEHD) was noticeably lower and did not exceed 0.10 failure/km · a.

Nearly 80% of pipe damage (both in Brzeg and Opole) have to be attributed to the cracks and perforation (corrosion pits) in the pipe material.

4.3. ANALYZING THE DURATION OF FAILURE

Another parameter affecting the reliability level of networks is the duration of failure expressed in terms of the availability factor.

As previously mentioned, the average time of failure T_f includes the time of repair preparation T_{rp} and the duration of damage removal T_{dr}.

The parameter T_{rp} refers to the time span between the appearance of damage and the moment at which damage removal starts. In engineering, consideration is given to the time when the pipe failure was reported, which is not necessarily equivalent to the real time when pipe failure commenced. The time of repair preparation includes the time needed to get to the place of failure, the time required for localizing the failure, the time of selecting appropriate tools and materials, and in some instances the queuing time (because other repairs have been given higher priority).

The duration of damage removal T_{dr} depends on a variety of factors, e.g. the type of the pipe conduit (material, diameter, condition), the type and size of damage, the depth reached by pipes, the soil and water conditions, atmospheric conditions, to name just a few of them.

As it can be inferred from the data of table 3 and table 4, the duration of failure T_f was longer in Opole than in Brzeg, ranging from 13.7 to 34.9 h (on an average 22.6 h) and from 5.7 to 9.4 h (on an average 7.0 h), respectively.

The extended time of failure in Opole should probably be attributed to the higher frequency of failure f_f and to a longer pipeline length, but primarily to the very long time of repair preparation, which varies between 5.7 and 21.3 h (on an average 12.4 h). When damage was reported before a national or religious holiday, or before the weekend, repair work was very often postponed.

In Brzeg, repair work was normally started immediately after the failure was detected or reported, so the time of repair preparation ranged between 0.5 and 2.2 h (on an average 1.3 h).

The average time of damage removal was also longer in Opole (T_{dr} from 8.0 to 13.8 h (on an average 10.2 h) than in Brzeg (T_{dr} from 4.8 to 8.9 h (on an average 5.6 h).

In Opole, the time of repair preparation was always longer than the time of damage removal.

In both the towns, the duration of failure showed a tendency to decrease.

4.4. ANALYSIS OF AVAILABILITY FACTORS

Making use of the information about the frequency of damage (f_f), the average serviceability (T_s) of the water pipes between failures (equation (5)), the availability factors (equations (3) or (4)) in particular years and in Period I and Period II were calculated for the water-pipe networks of Brzeg (table 3) and Opole (table 4).

The values of K were assessed without taking into account the reliability structure of the water-pipe networks, and they were used for the purpose of comparison.

As it may be inferred from these comparisons, the network of Brzeg showed a higher reliability than the network of Opole. The average values of the availability factors were

in Brzeg: $K = 0.981749$ (Period I) and $K = 0.989011$ (Period II);

in Opole: $K = 0.910672$ (time span of 1996–2001).

The low value of the availability factor of the water-pipe network of Opole resulted from the long duration of failure, despite the comparatively low failure rate.

In Brzeg, a higher reliability level was achieved in Period II owing to the reduction of the failure factors (because of decrease in H_{max} and ΔH) and of the duration of failure as compared to Period I.

The reliability levels of both water-pipe networks investigated were compared with the required reliability level K_r calculated in terms of equation (2). The comparisons were made by adopting the K_r(WSS) values from table 1 (according to [1]) and table 2 (according to [4]), after having established the category of reliability for the WSSs investigated and by assuming that $Q \approx Q_n$.

Thus, the required reliability level for the water-pipe network in Brzeg (about 40000 inhabitants) is

$K_r \geq 0.956563$ according to [1] for Category IV,

$K_r \geq 0.991747$ according to [4] for Category II.

These values indicate that the reliability level of the water-pipe network in Brzeg is considerably higher than the one required by Soviet standards [1] and lower than the one postulated by Polish investigators [4].

The required reliability level for the water-pipe network in Opole (131000 inhabitants) amounts to

$K_r \geq 0.986963$ according to [1] for Category III,

$K_r \geq 0.995882$ according to [4] for Category II.

In the time span of 1996–2001, the reliability level of the water-pipe network in Opole is lower than the values postulated by [1] and [4].

5. SUMMARY

In-service investigations of two water-pipe networks have revealed that their reliability levels depend primarily on the frequency and duration of failure. These parameters not only affect the operation costs and the size of water loss, but also create nuisance to the users.

For these reasons it is necessary to take any actions that aim at reducing the failure rate and the resulting effects.

The furtherance of comprehensive investigations into the water supply systems which are in service now, as well as a thorough analysis of the available literature in order to establish the desired reliability level for the WSS, has taken on a sense of urgency, because the postulated values are confusing.

REFERENCES

[1] WIECZYSTY A., *Niezawodność systemów wodociągowych i kanalizacyjnych*, cz. I i II, Skrypt Politechniki Krakowskiej, Kraków, 1990.

[2] WIECZYSTY A., IWANEJKO R., *Wyznaczanie wymaganego poziomu niezawodności obiektów systemu zaopatrzenia w wodę*, GWiTS, 1996, 2, 54–58.

[3] WIECZYSTY A., IWANEJKO R., *Metoda określania wymaganego poziomu niezawodności elementów systemu zaopatrzenia w wodę*, Gospodarka Wodna, 1998, 7, 268–272.

[4] KWIETNIEWSKI M., ROMAN M., KŁOSS-TRĘBACZKIEWICZ H., *Niezawodność wodociągów i kanalizacji*, Arkady, Warszawa, 1993.

[5] HOTLOŚ H., *Ograniczenie ciśnienia w sieci wodociągowej jako czynnik zmniejszający uszkadzalność i koszty napraw uszkodzeń przewodów*, GWiTS, 1999, 5, 180–184.

[6] HOTLOŚ H., *Analiza strat wody w systemach wodociągowych*, Ochrona Środowiska, 2003, 1, 17–24.

[7] HOTLOŚ H., *Badania eksploatacyjne wpływu wysokości ciśnienia i materiału rur na uszkadzalność sieci wodociągowej*, GWiTS, 2000, 11, 402–407.

[8] HOTLOŚ H., *Wpływ modernizacji pompowni na parametry eksploatacyjne sieci wodociągowej*, Ochrona Środowiska, 2002, 4, 27–31.

[9] SIENKIEWICZ I., *Ocena uszkadzalności przewodów sieci wodociągowej w Opolu na podstawie badań eksploatacyjnych*, manuscript of the paper for MSc degree, Wydział Inżynierii Środowiska Politechniki Wrocławskiej, Wrocław, 2002.

POZIOM NIEZAWODNOŚCI MIEJSKICH SIECI WODOCIĄGOWYCH

Przedstawiono metody oceny wymaganego poziomu niezawodności systemów zaopatrzenia w wodę. Analizę poziomu niezawodności przeprowadzono na podstawie wyników otrzymanych podczas badania wieloletniej eksploatacji sieci wodociągowych w Brzegu i Opolu. Określono wskaźniki uszkodzeń i średnie czasy niesprawności przewodów wodociągowych oraz wartości wskaźników gotowości badanych sieci, które porównano z wymaganym poziomem niezawodności według różnych autorów.

Wskazano na konieczność zmniejszenia uszkadzalności i czasu niesprawności sieci wodociągowych, zwłaszcza w Opolu, w celu zwiększenia poziomu niezawodności.

Konieczne jest kontynuowanie wszechstronnego badania istniejących systemów wodociągowych, aby ustalić wymagany poziom niezawodności, gdyż proponowane obecnie jego wartości są bardzo zróżnicowane.