TECHNICAL TRANSACTIONS | **CZASOPISMO TECHNICZNE**
ENVIRONMENT ENGINEERING | ŚRODOWISKO

1-Ś/2013

RYSZARDA IWANEJKO*

RISK CALENDAR AS A SUPPLEMENT OF A BASIC RISK ANALYSIS IN A WATER SUPPLY SYSTEM

KALENDARZ RYZYKA JAKO UZUPEŁNIENIE PODSTAWOWYCH ANALIZ USZKADZALNOŚCI SIECI WODOCIĄGOWEJ

Abstract

During the research work, a failure analysis in the water supply systems was performed with respect to different time scale. The results of such analyses provide information on failures' distribution over time, occurrence of the so called 'black series' (i.e. series of days with numerous failures) or days without failures. Therefore, they may be useful in the validation of a number of maintenance schemes and the selection of the optimal time for the necessary maintenance actions and pre-scheduled repairs of the water supply system. They may also be of a substantial practical value for the operator, while preparing the so called risk calendar.

Keywords: water distribution system, system failures

Streszczenie

W artykule przeprowadzono analizy uszkodzeń sieci wodociągowej w odniesieniu do różnych jednostek czasu. Wyniki takich analiz dostarczają informacji o rozkładzie uszkodzeń w czasie, o występowaniu tzw. czarnych serii (czyli kolejnych dób z dużą liczbą uszkodzeń) czy dób bezuszkodzeniowych. Mogą więc być przydatne przy weryfikacji liczby brygad remontowych, przy praktycznym wyborze okresów optymalnych dla przeprowadzania koniecznych prac konserwacyjnych i remontów planowych sieci wodociągowej. Dlatego mogą posłużyć do sporządzenia tzw. kalendarza ryzyka i mieć dla eksploatatora sieci duże znaczenie praktyczne.

Słowa kluczowe: sieć dystrybucji wody, uszkodzenia sieci

---

* Ph.D. Ryszarda Iwanejko, Institute of Water Supply and Environmental Protection, Faculty of Environmental Engineering, Cracow University of Technology.

1. Introduction

Water supply systems have become the subject of many research works and analyses. They look at them both from the perspective of reliability of function (early seventies of the 20th century) and from the safety and risk perspective (middle 90s). The history of these works is summarized in the paper [1]. Initially, the scope of the reliability analysis of the water supply systems was very limited due to a low development level of the field and a lack of satisfactory failure data. The data was collected for specific municipal services rather than for a broader applicable reliability analysis. However, in recent years, a growing number of water utilities began to appreciate the availability of the ‘at source’ information during management and planning processes. The utilities apply widely available computer techniques and generate huge databases. The basic measure used to estimate water system conditions is its failure rate λ_0. This parameter is defined as a number of failures within the water system per time unit and length unit (usually per 1 km and 1 year). In the literature [1, 2] there are values of λ_0 that cannot be exceeded. The range and degree of detail in a contemporary analysis of water system failures depends not only on the scope and the accuracy of the information gathered by the operator, but also on the creativity and knowledge of the analyst. The most common are general analyses, which determine the parameter λ_0, for the entire system, in consecutive years, or just for some particular sections, taking into account their functions (mains, distribution lines, connections) or material (cast iron, steel, PVC, etc.) together with variability analyses. Additionally, the possibility of generation of risk maps came to light [3]. They provide information on the spatial distribution of failures. The final outcome of all activities combines the information on failures that reflect on the actual water system conditions, not only at a particular utility, but also at a nationwide scale [2, 4].

It is known that failures occur in a dynamic way [5] and the process parameters change in time. Therefore, the paper presents mostly results of a water system failure analysis function over time that may be useful while making a risk calendar. The key parameter in this analysis is not a relative failure rate λ_0, calculated per time and length units, but a number of failures k related to different time units, only (year, month and day). Such analyses, though cannot help to compare failures in different water systems nor to check the limiting criterion λ_0, may still have a practical meaning for the operators. They may be useful during the validation of a maintenance team size and during the actual selection of the optimal periods for necessary maintenance actions and pre-scheduled repairs of the water system. Particularly important may be the knowledge on: the probability of occurrence of the so-called extreme days (with a large number of failures); probability of occurrence of ‘black series’ (series of days with a large number of failures); the probability of occurrence of failure-free days. The parameters determined in this paper are empirical. Assuming that an operation mode or climate conditions will not change substantially, a similar pattern of failures may be expected in future.

2. Short characteristic of the system

Further analyses will be conducted for the water distribution system located in one of the cities of Southern Poland. Municipal Water and Sewage Works (MWSW) of this city provides water for over 850 thousand inhabitants. Water is supplied to the consumers through a complex distribution system. The total length of the system in 2010 was almost 2037 km and consisted of: transit pipes and mains of 350–1200 mm diameter (11% of the total system length in 2010), distribution lines of 325–80 mm diameter (ca. 64%) and household connections of 100–25 mm (ca. 25%). Most of the pipes have been made of steel (ca. 30.4% of all pipes), cast iron (ca. 26%) and plastic (PVC 21.6%, PE 18.6%). The rest of the pipes (ca. 3.4%) are made of asbestos cement or lead. About 15% of pipes have been used for less than 10 years while 18% for 11–20 years; a large number of pipes (67%) has been in operation for at least 20 years, including some that are no less than 50 years old (ca. 7%).

Data obtained from the MWSW of the city provided the grounds for a more detailed analysis [6]. Operational reports, which were used for further research, were collected in a MS-Excel database. In this database, recorded failures were completed with information on the date of repair, the name of the street where the pipe is located, the failures item (pipe, connection, hydrant, gate, etc.), the pipe diameter, the material (cast iron, steel, etc.) and the repair action (replacement**,** cut, tightening, etc.). It is worth noting that it is the dates of repairs that are noted rather than the dates of the failure occurrence. Recorded water system failures are dealt with as soon as possible – their repair could not be postponed. Breakdowns of the highest priority must be repaired quickly. Those that are less important and of lower priority, even if reported on a day preceding a holiday, could be taken care of after several days, especially when all maintenance teams are occupied. However, in such circumstances repairs may be delegated to third party companies. When delays occurred, the reasons were objective such as e.g. difficult access to the site. There have surely been cases of less important or complex failures being repaired much later after having been reported, but it did not result in water shortages or pose any danger or difficulties for consumers. It can be assumed that the analysis of repaired failures instead of occurrences does not significantly influence the accuracy of the final conclusions related to water supply availability. Therefore, the number of repairs shall hereinafter be considered equal to the number of occurred failures.

The following database analysis is not yet complete through it contains information on failures repaired by the third parties. In the database, in certain records, some information such as the type of materials used or the pipe's diameter are missing. Also some given data are insufficient – e.g. in case of overlapping diameters of distribution lines and household connections (80–100 mm). Additional information should be added on which pipes failed. There are following reasons for missing data:

1) failure of fittings,
2) failure at connection points (change of a pipe diameter),
3) repair involved tightening (sealing),
4) data is gathered during failure occurrence i.e. in different weather conditions and with a time pressure. As a result, complete and highly reliable analysis cannot be conducted.

3. Analysis of the number of water system damages in time

In 2006–2011 the number of recorded and repaired failures *k* was subject to increasingly detailed analysis, relating to years, months or days. However, in the text only the most interesting data, graphs and results have been presented.

3.1. Yearly analyses

Figure 1 shows the changes in the number of failures in particular years. On average, $k = 1354$ failures were repaired per year. In the years 2008 and 2011, the lowest number of failures was recorded, whereas the highest was reported in 2006. Pipes were the most often damaged items (ca. 89.9% of the total number of failures), while damage of gates constituted about 7.4% and hydrants ca. 2.5%. The rest, ca. 0.2%, was described as 'others' (drains, hand pump, valve, etc.).

The length of the system itself was growing relatively slowly (20–40 km/year on average – during the analysis, it gained almost 110 km, that is 6% comparing to 2006) and quite comparable to the average failure rate λ_0 (Fig. 1). The average failure rate was $\lambda_0 = 0.7$ [1/km × year] and was never higher than 1 [1/km × year], which is the figure considered as acceptable by western experts [1]. During the last three years, one can notice the decrease of the failure rate λ_0. Unfortunately, because of the incomplete database it was not possible to analyze the changes in the failure rates of mains distribution lines and household connections separately.

Fig. 1. Failure rates λ_0 and number of failures k in the city water supply system (2006–2011)

3.2. Monthly analyses

It has been observed that the number of failures depends on the month, or more to the point on the seasons. (Fig. 2). As it could have been expected, in winter time (January, December) the number of failures is almost twice as high as in summer. The highest monthly failure rate was observed in January (0.088 [1/km × month]) and December (0.086 [1/km × month]), whereas the lowest was observed in May and June (0.04 [1/km × month]). If the failure rate stays at the same level during the whole year as it does in the winter, it would exceed the acceptable value of $\lambda_0 = 1$ [1/km × year] and according to western standards, the system would be qualified as one that requires renovation.

A question which arises is whether there is a connection between the type of pipe material and the time of year. As it has been mentioned, there is significant information missing in the collected data. For example, in May 2008 in 67.5% cases (50 out of 74 breakdowns) the material was not indicated, while at the turn of 2009 and 2010 ca. in 43% of cases, there was no information on the construction material. Because of the incomplete maintenance services records, general data analysis is quite difficult, nonetheless, it still may lead to interesting conclusions. When taking into account all the data (Fig. 3a) as well as when excluding incomplete records (no information on the pipe material, Fig. 3b), it may be concluded that cast iron pipe failures were the most common in the winter (up to even 60% of the total failures), whereas in the summer, it was the steel pipe failure (up to 50% of all failures). About 23% of records were ignored because of them being incomplete (from 13.9% to 31.1%, depending on the month), which is a significant part of the database. The analysis was conducted despite the missing information. The case was then analyzed, failures with missing pipe material records were distributed between all materials, proportional to the actual material structure of the system. The results differed only slightly (by few percent) from the results obtained when such failures were ignored. Additionally, a substantial predomination of failures of cast iron pipes in winter and steel pipes in summer was true, in all cases.

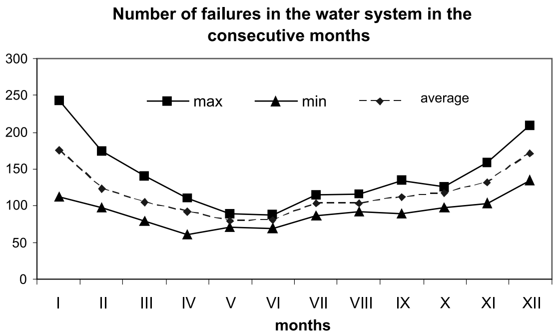

Fig. 2. Number of failures *k* in the water supply system in consecutive months

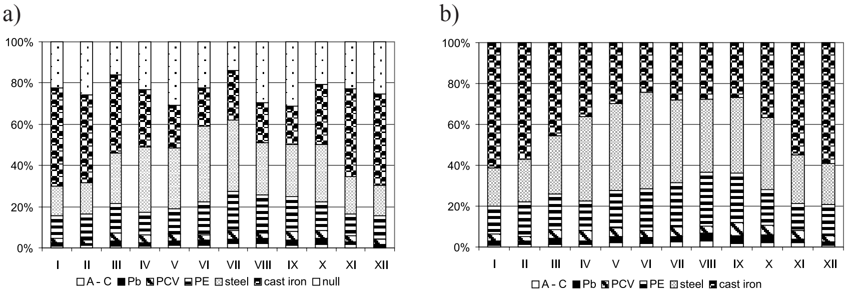

Fig. 3. Failures distribution of in the *X* water distribution system as a function of the month and pipe material: a) all the data b) incomplete information on the material is ignored

In the data base, a number of cast iron pipe sections have been identified (with a diameter < 100 mm), which broke more often in winter; for instance, one of the sections broke five times in winter while only once in summer. Failures may be caused by shallow pipe placement, severe and snow-less winters and low water velocities at night. Cast iron pipes showed the highest failure rate λ_0. Although due to missing information in the database, precise calculations were not possible, some additional research was carried out.

The results for cases where failures with the missing material information have been distributed between all other materials proportionally to the system material structure, are presented in Fig. 4. The values λ_0 determined in subsequent years indicate a decreasing trend for cast iron due to system renovations, replacement of pipes with PVC/PE pipes and seals. On the other hand, failures rates for steel, PE and PVC do not undergo any substantial changes.

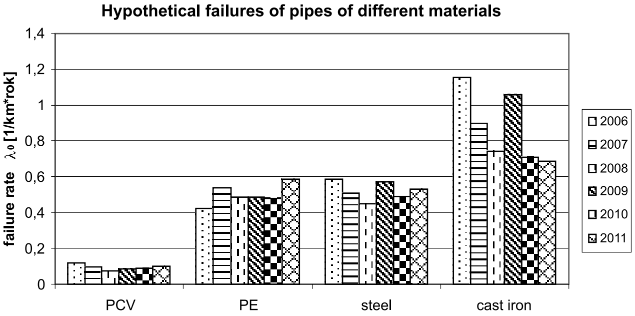

Fig. 4. Failure rates in the water supply systems of different materials – incomplete data distributed proportionally to the material structure of the *X* system

Because of the missing information, a similarly complex situation occurred when analyzing the relationship between the number of failures for different pipe diameters and the actual season. In this case, incomplete data was only 10.5% of all the records in the database (8–16%, depending on month, Fig. 5), which is almost twice less than in the previous category. Research has been conducted both by including all available data and by excluding incomplete records. In both cases, it has been established that the largest number of failures (ca. 60%) occurred on small diameters (25–100 mm), i.e. on household connections and some distribution lines. Moreover, in the summer, a bigger number of failures occurred on the

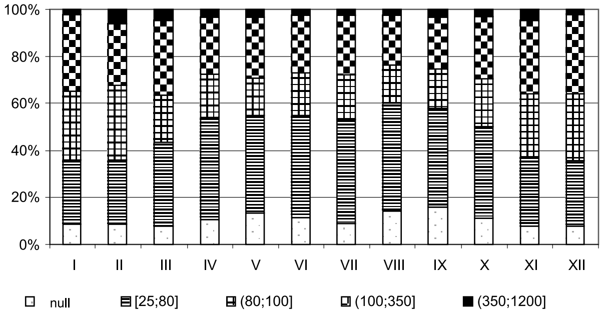

Fig. 5. Percentile distribution of a number of failures in the *X* water supply system as a function of month and diameter (all data included)

smallest diameters (25–80 mm); the results of both analyses differ by only a few percent. For instance, in winter, 25–30% of all damages concerned pipes of 25–80 mm diameter whereas between April and September it was 42–53%. Such an outcome may result from the fact that the data base does not differentiate between the real failures and general and preventive repairs carried out in summer time. Although based on this data it is possible to draw the general conclusion, these particular examples show how important it is to gather complete information, without which, it is difficult to make a correct judgment.

3.3. Daily analyses

The number of failures (repaired) changes also on the daily basis. The largest number of system failures, 18 failures/day, were repaired on January 9th, 2009 (Fig. 6). It is also noticeable that there were several days when at least 10 failures were repaired.

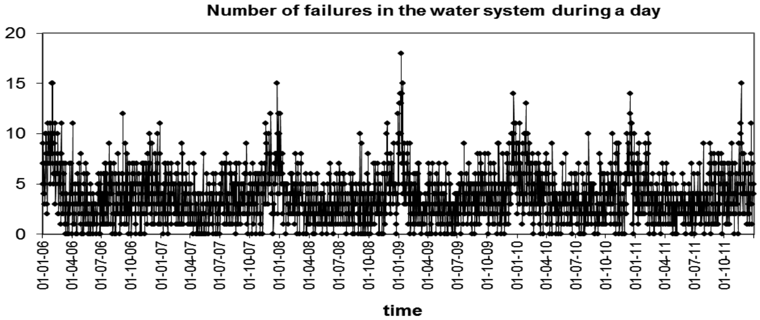

Fig. 6. The number of failures in the *X* water distribution system that were repaired in the subseqent days (2006–2011)

The maximum number of daily failures in every month has been illustrated in Fig. 7. However, in every month there were days when no single failure was repaired. The lowest variability and the lowest number of failures were recorded in the summer (May, June and July), whereas the highest variability was found in the winter (particularly in January).

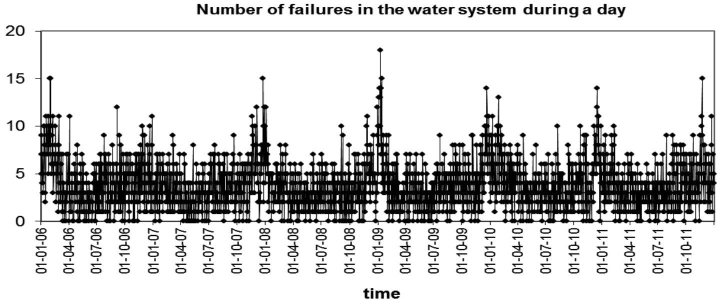

Fig. 7. The maximum number of failures repaired in water distribution system per day (2006–2011)

What may be important for the operator is information about the occurrence of the so-called extreme days (with the lowest or the highest number of failures). Information on the water system leads to the conclusions that 3 repairs per day was the most common result during the year (annual average, 60 days with 3 repairs. A lower number of failures (*k* = 0, 1, 2) occurred rarely – on avarage 25, 42 and 53 days per year. In the winter, however, the most common daily result was 4–5 repairs per day (in January and December, there were 9 days with such an average). Also in winter, a smaller number of failures (*k* = 0, 1, 2, 3) occurred rarely – on average once, 3, 5 and 7 times per year (Fig. 8).

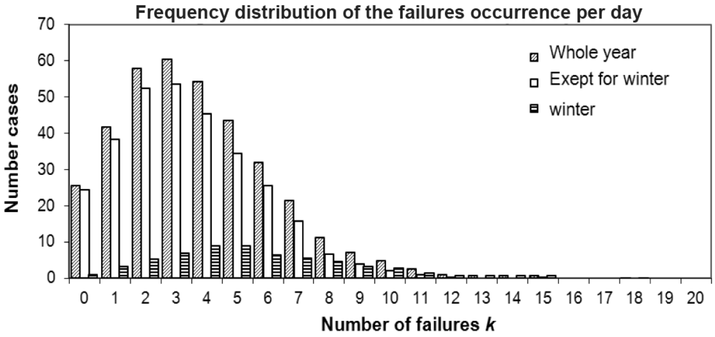

Fig. 8. Distribution of the number of failures in the water system over 1 day (2006–2011)

Taking into account the length of the selected time periods, one can determine the empirical probability of occurrence, and then an empirical probabitity of exceeding the given number of failures per day (Fig. 9). The probabilities of occurrence of over 5 failures per day are quite similar for a whole year and for the months from February to November. They are 0.226 and 0.185 respectively, while during the winter it reaches 0.44. This indicates that during 44% of the winter (almost 27 days), more than 5 failures were repaired daily. By analogy, the probabitity of exceeding *k* = 10 per day can be assessed. They are 0.016 during the whole year, 0.073 in winter and only 0.004 in the other months. It means that the number of days when at least 10 failures were repaired were: 5.3 days – average year, 4.5 days – winter and 1.3 days during the rest of the year.

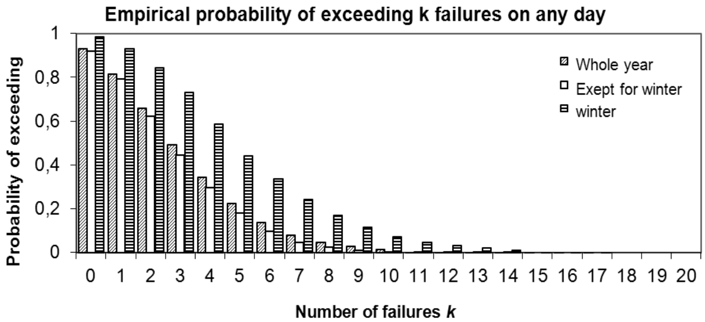

Fig. 9. Empirical probabitity of exceeding the failure number in the *X*'s water system on any day

Distribution of days with a significant number of repairs does not yet include the information on the occurrence of so-called 'black series' (series of days with a high number of failures). What may be important for the operator is the information if in previous years there had been such series and what was the duration of the longest one. Regarding the analyzed system (Fig. 10), the most common were days when at least 5 failures were repaired ($k \geq 5$) and on days preceding and following, fewer failures were fixed. On average, 34.5 such series ($k \geq 5$) of length $i = 1$ per year were recorded. A similar series of $i = 2$ occurred on average 13 times a year; a series of $i = 10$ was recorded once during the 6-year period.

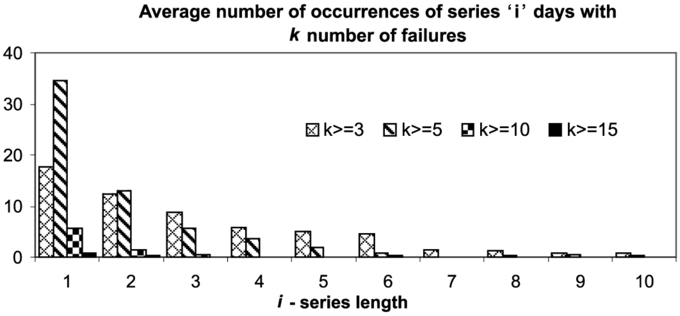

Fig. 10. Average number of occurrences of series – *i*-days per year, when at least *k* failures in the *X*'s water system were repaired

The empirical probability of series duration is illustrated in Fig. 11. It shows that, for example if on any day $k \geq 15$ failures are fixed (the empirical probability of such an event is $p_{k \geq 15} = 0.00273$), the probability that on the following day also at least 15 failures would need repairing is $p_{k \geq 15, k \geq 15} = 0.2$. Although such series probabilities are high, it has to be remembered that these are conditional probabilities**.** An actual unconditional probability of occurrence of two subsequent days, when at least 15 failures are repaired is only $p_{k \geq 15} \times p_{k \geq 15, k \geq 15} = 0.00273 \times 0.2 = 0.00055$. More useful is an analysis of series of days when at least 5 failures were repaired ($k \geq 5$). The probability (conditional) that the length of such a series would be $i = 1$ is about $p_{k \geq 5} = 0.57$, while the probability that a series length (if any) would be $i = 2$ or $i = 3$ is 0.21 and 0.09, respectively. Unconditional empirical probabilities of such series are respectively 0.465, 0.138 and 0.031.

Fig. 11 only presents the results for series of $i \leq 10$. However, also exceptionally long series may occur.

The longest are those in which small numbers of failures were repaired daily (e.g. for $k \leq 1$, the maximum length of a series is $i_{\max} = 137$, for $k \leq 2$ is $i_{\max} = 56$, and for $k \leq 3$ $i_{\max} = 37$). The latter result indicates that during the evaluated period, the longest period, when at least 3 failures per each following day were repaired, was 37 days. Similarly, over 25 days, at least 5 failures/day were repaired and over 6 days, 10 failures/day (Fig. 12). The longest series and those with the highest number of failures occurred most often during winter. The longest series when no failures were repaired ($k = 0$) was recorded in April and May (maximum length $i = 3$).

On average, there were almost 25 days per year, when no failures were repaired – the highest number of such days was recorded in May (4.2 days), April, June and November

(Fig. 13). The maximum number of consecutive failure-free days ($k = 0$) was $i = 3$ (series of failure-free days). Assuming that no repairs means no failures to be fixed, other actions (maintenance, pre-scheduled repairs) could be set for these months. However, as it can be easily predicted, the smallest number of failure-free days was recorded in the winter (January, December).

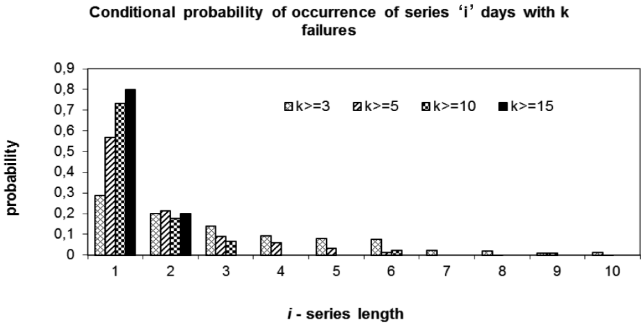

Fig. 11. Distribution of the probability of occurrence of series of *i* days, during which at least *k* failures occurred.

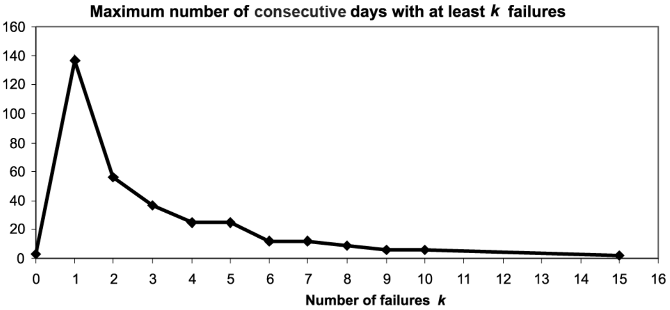

Fig. 12. The maximum number of consecutive days when the number of repaired failures in the *X* water system was at least *k*

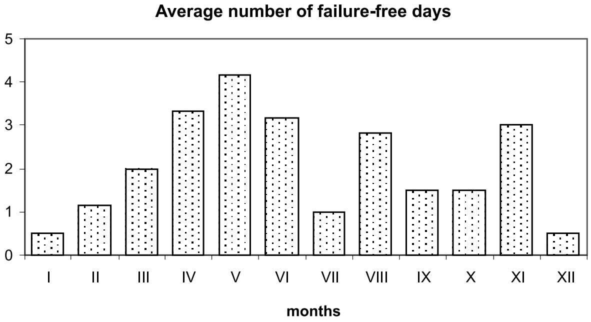

Fig. 13. Failure-free days in the *X*'s water system

On Mondays, maintenance teams are charged with twice as many tasks as on Saturdays and Sundays (Fig. 14). Also, in the winter, the number of failures requiring repair in the following days of the week is on average, twice as high as in other months.

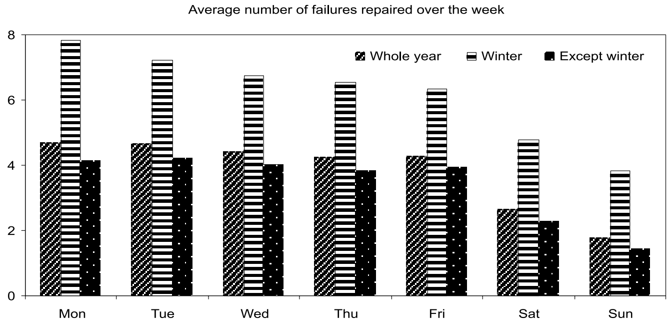

Fig. 14. Distribution of the failures repaired on particular days of the week in the *X* water system

The analysis leads to the following conclusions. The number of failures *k*, and the average failure rate λ_0, show a significant time dependency. This is a strong argument for performing deeper analyses, with more emphasis on yearly, monthly and daily results. Properly conducted research allows for identifying trends, seasonal variations or daily distributions of failures in different times of the year. It is obvious that the more precise the database, the more detailed the analyses and the more reliable results one may expect.

The presented results are only used as examples to suggest how water system failure calendars should be created. Similar analyses could be conducted for particular regions or zones of large dwellings. An analysis should also try to indentify reasons for extremely high numbers of failures per day or for series of failure (e.g. extreme weather phenomenon or system operation at high pressure, etc.).

4. Conclusions

- Comprehensive analysis of water system failures should be based on complete databases with distinguished records on occurred and repaired failures.
- Analyses of failures over time can be conducted for consecutive years, months and days – to generate a risk calendar.
- Nowadays, gathering complete and sufficiently detailed information on occurred and repaired failures does not pose problems of a technical or organizational nature. The reasons for poor databases are often the lack of conviction of their suitability or low staff competences. They can be easily dealt with by the operator and do not generate high costs.
- Incomplete databases make it difficult to draw right conclusions. On the other hand, ignoring their incompleteness would result in false conclusions.
- For process analyses, no particular programs are required – the above results were obtained with EXCEL and a few simple macros. Although discussion of results should be assigned to an analyst, in many water utilities, well-trained personnel may do this job.

- Results from analyses originally conducted to help in the creation of a 'risk calendar' may also prove useful for the optimal management of water system operation or better work planning (maintenance, pre-scheduled repairs). The analyses help to identify whether or not there is a seasonal dependence in failure rates to determine the average number of failures in a particular period of time (year, month, day), the probabitity of exceeding a given number of failures or the probabitity of 'black series' occurrence.
- In general, the numbers of repaired failures on consecutive days may not be independent. The dependence, over short periods of time, is due to the fact that not all reported failures are fixed immediately. That is the case especially for low priority failures reported at the end of the week and/or on days preceding holidays. Such conditions may also occur during severe winters without snow, when on a few consecutive days there are numerous failures and not enough maintenance teams**.** Then also, the repair time is longer than average. The lack of independence in longer periods of time is the a result of the seasons' influence on failure occurrence (seasonality).
- The data reliability depends on a complete data base. Additionally, a lack of a clear distinction between random failures and preventive and general repairs causes an increase in the failure rate λ_0. It may also lead to false conclusions i.e. more work on small diameter pipes in summer results not from a higher failure rate, but from the fact that most new connections are carried out in summer.

The scientific work was financed from funds for research into a self-development project No N R14 0006 10 entitled 'Development of comprehensive methodology for the assessment of the reliability and safety of water supply to consumers'.

References

[1] Kwietniewski M., Rak J., *Niezawodność infrastruktury wodociągowej i kanalizacyjnej w Polsce*, Komitet Inżynierii Lądowej i Wodnej PAN, Studia z zakresu inżynierii nr 67, Warszawa 2010, 27-32.

[2] Rak J., *Podstawy bezpieczeństwa systemów zaopatrzenia w wodę*, Monografie Komitetu Inżynierii Środowiska PAN, vol. 28, Lublin 2005, 113-119.

[3] Tchórzewska-Cieślak B., Wybraniec A., *Metoda wyznaczania obszarów ryzyka awarii w podsystemie dystrybucji wody*, INSTAL 10/2008, 99-101.

[4] *Wodociągi i kanalizacja w Polsce. Tradycja i współczesność*, red. Dymaczewski Z., Sozański M., Polska Fundacja Ochrony Zasobów Wodnych, Poznań–Bydgoszcz 2002, 367-422.

[5] Iwanejko R., *Dynamiczne ryzyko związane z niesprawnością sieci wodociągowej*, Aktualne zagadnienia w uzdatnianiu i dystrybucji wody, Gliwice 2011, 297-306.

[6] *Dane o uszkodzeniach sieci wodociągowej uzyskane z MPWiK miasta X. 2012.*