Appendix 2

Katarzyna Pietrucha-Urbanik, PhD, Eng.
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SUMMARY

concerning achievements in scientific and research work

1. PERSONAL DATA

First name and surname: **Katarzyna Pietrucha-Urbanik**

2. TITLES AND DEGREES HELD

VII. 2007 Professional title: Msc Eng.
Scientific discipline: Environmental Engineering
Diploma: Water Supply and sewage Disposal
Rzeszów University of Technology
The Faculty of Civil and Environmental Engineering
Subject of the MSc thesis: *Analysis of the impact of sewage systems on the water quality of the receiver*
MSc thesis advisor: **Prof. Józef Dziopak, DSc, PhD, Eng.**
Reviewer: **Prof. Janusz Rak, DSc, PhD, Eng.**

IV.2014 r. Degree: PhD Eng. In technical sciences
Scientific discipline: Environmental Engineering
Bialystok University of Technology
The Faculty of Civil and Environmental Engineering
Subject of the doctoral thesis: *Methodology for determining the guarantee in collective water supply systems*
Thesis defended with distinction awarded by the Council of the Faculty of Civil and Environmental Engineering at the Białystok University of Technology
Doctoral thesis advisor: **Prof. Janusz Rak, DSc, PhD, Eng.**
Reviewers: **DSc, PhD, Eng. Dariusz Kowalski prof. of Lublin University of Technology,**
Prof. Rafał Miłaszewski, DSc, PhD, Eng.

3. INFORMATION ON PREVIOUS EMPLOYMENT IN RESEARCH UNITS

2007-2014 an assistant in the Department of Water Supply and Sewage Systems, the Faculty of Civil and Environmental Engineering of the Rzeszow University of Technology.

from 2014 an assistant professor in the Department of Water Supply and Sewage Systems, the Faculty of Civil and Environmental Engineering and Architecture of the Rzeszow University of Technology.

4. THE INDICATION OF THE ACHIEVEMENT RESULTING FROM ART. 16 ITEM 2 OF THE ACT DATED ON THE 14TH OF MARCH 2003 ON DEGREES AND ACADEMIC TITLES AND ON DEGREES AND TITLES IN THE SCOPE OF ART (THE OFFICIAL JOURNAL NO. 65, ITEM 595 WITH SUBSEQUENT AMENDMENTS)

4.1. TITLE OF THE SCIENTIFIC ACHIEVEMENT

The scientific achievement, determined in accordance with the applicable "Act on academic degrees ... art. 16, item 2 " is a single issue series of publications titled: **FAILURE RISK ANALYSIS AND ASSESSMENT OF THE WATER SUPPLY NETWORK**

4.2. SUMMARY OF SINGLE ISSUE PUBLICATIONS CONSTITUTING BASIS FOR THE SCIENTIFIC ACHIEVEMENT

No.	The title of the publication
1 A Journal List	**Pietrucha-Urbanik K.,** Studziński A. Case study of failure simulation of pipelines conducted in chosen water supply system, 2017, EKSPLOATACJA I NIEZAWODNOSC-MAINTENANCE AND RELIABILITY, Vol.19, No. 3, pp. 317-323 ISBN/ISSN: 1507-2711 Number of points in the publication year: 25 pts. Percentage of participation in the publication: 60% Number of points after taking the habilitated doctor's participation into account: 15 pts. Impact factor in the publication year: 1.383 (IF), 1.296 (IF_{5years}) $SNIP_{2017}$ according to Scopus: 1.363
2 A Journal List	**Pietrucha-Urbanik K.,** Studziński A. Selected Issues of Costs and Failure of Pipes in an Exemplary Water Supply System, 2016, ANNUAL SET THE ENVIRONMENT PROTECTION, Vol. 18, pp. 616-627 ISBN/ISSN: 1506-218X Number of points in the publication year: 15 pts. Percentage of participation in the publication: 60% Number of points after taking the habilitated doctor's participation into account: 9 pts. Impact factor in the publication year: 0.705 (IF), 0.545 (IF_{5years})

No.	The title of the publication
	SNIP$_{2017}$ according to Scopus: 0
3 A Journal List	**Pietrucha-Urbanik K.**, Żelazko A. Approaches to Assess Water Distribution Failure. 2017, PERIODICA POLYTECHNICA-CIVIL ENGINEERING, Vol. 61, No. 3, pp. 632-639 ISBN/ISSN: 0553-6626 Number of points in the publication year: 15 pts. Percentage of participation in the publication: 60% Number of points after taking the habilitated doctor's participation into account: 9 pts. Impact factor in the publication year: 0.636 (IF), 0.640 (IF$_{5years}$) SNIP$_{2017}$ according to Scopus: 0.669
4 Indexed in WoS and Scopus	**Pietrucha-Urbanik K.** Assessing the costs of losses incurred as a result of failure [w:] Dependability Engineering and Complex Systems - Proceedings of the Eleventh International Conference on Dependability and Complex Systems DepCoS-RELCOMEX. June 27-July 1, 2016, Brunów, Poland, (eds.) Zamojski W., Mazurkiewicz J., Sugier J., Walkowiak T., Kacprzyk J., 2016, London: SPRINGER INTERNATIONAL PUBLISHING SWITZERLAND, Vol. 470, pp. 355-362 ISBN/ISSN: 978-3-319-39638-5 Number of points in the publication year: 15 pts. Percentage of participation in the publication: 100% Number of points after taking the habilitated doctor's participation into account: 15 pts. Impact factor in the publication year: 0 (IF), 0 (IF$_{5years}$) SNIP$_{2017}$ according to Scopus: 0.338
5 Lista A	**Pietrucha-Urbanik K.**, Tchórzewska-Cieślak B. Failure risk assessment in water network in terms of planning renewals - a case study of the exemplary water supply system, 2017, WATER PRACTICE AND TECHNOLOGY, Vol. 12, No. 2, pp. 274-286 ISBN/ISSN: 1751-231X Number of points in the publication year: 15 pts. Percentage of participation in the publication: 60% Number of points after taking the habilitated doctor's participation into account: 9 pts. Impact factor in the publication year: 0 (IF), 0 (IF$_{5years}$)

No.	The title of the publication
	SNIP$_{2017}$ according to Scopus: 0.278
6 A Journal List	**Pietrucha-Urbanik K.** Failure analysis and assessment on the exemplary water supply network 2015, ENGINEERING FAILURE ANALYSIS, Vol. 57, pp. 137-142 ISBN/ISSN: 1350-6307 Number of points in the publication year: 30 pts. Percentage of participation in the publication: 100% Number of points after taking the habilitated doctor's participation into account: 30 pts. Impact factor in the publication year: 1.358 (IF), 1.289 (IF$_{5years}$) SNIP$_{2017}$ according to Scopus: 1.363
7 A Journal List	**Pietrucha-Urbanik K.**, Tchórzewska-Cieślak B. Approaches to Failure Risk Analysis of the Water Distribution Network with regard to the Safety of Consumers, 2018, WATER, No. 10(11), 1679 ISBN/ISSN: 2073-4441 Number of points in the publication year: 30 pts. Percentage of participation in the publication: 60% Number of points after taking the habilitated doctor's participation into account: 18 pts. Impact factor in the publication year: 2.069 (IF), 2.25 (IF$_{5years}$) SNIP$_{2017}$ according to Scopus: 1.007
8 A Journal List	**Pietrucha-Urbanik K.**, Studziński A. Qualitative analysis of the failure risk of water pipes in terms of water supply safety, 2019, ENGINEERING FAILURE ANALYSIS, Vol. 95, pp. 371-378 ISBN/ISSN: 1350-6307 Number of points in the publication year: 35 pts. Percentage of participation in the publication: 60% Number of points after taking the habilitated doctor's participation into account: 21 pts. Impact factor in the publication year: 2.157 (IF), 2.148 (IF$_{5years}$) SNIP$_{2017}$ according to Scopus: 1.363
9 A Journal List	Studziński A., **Pietrucha-Urbanik K.**

No.	The title of the publication				
	Simulation model of contamination threat assessment in water network using the Epanet software, 2016, ECOLOGICAL CHEMISTRY AND ENGINEERING S-CHEMIA I INZYNIERIA EKOLOGICZNA S, Vol. 23, No. 3, pp. 425-433 ISBN/ISSN: 1898-6196 Number of points in the publication year: 15 pts. Percentage of participation in the publication: 40% Number of points after taking the habilitated doctor's participation into account: 6 pts. Impact factor in the publication year: 0.7 (IF), 0.815 (IF_{5years}) $SNIP_{2017}$ according to Scopus: 0.535				
10 B Journal List	**Pietrucha-Urbanik K.**, Tchórzewska-Cieślak B., Mohamed E. Cascading Failure Analysis in Order to Assess the Resilience of a Water Supply System, 2018, JOURNAL OF POLISH SAFETY AND RELIABILITY ASSOCIATION, SUMMER SAFETY AND RELIABILITY SEMINARS, Vol. 7, No.1-2, pp. 149-156 ISBN/ISSN: 2084-5316 Number of points in the publication year: 9 pts. Percentage of participation in the publication: 60% Number of points after taking the habilitated doctor's participation into account: 5.4 pts. Impact factor in the publication year: 0 (IF), 0 (IF_{5years}) $SNIP_{2017}$ according to Scopus: 0				
11 B Journal List	Rak J., **Pietrucha-Urbanik K.** Implementation of the Bow-Tie method to analyze the safety of water supply systems, 2017, GAS, WATER AND SANITARY TECHNIQUE, No.11/2017, pp. 453-457 ISBN/ISSN: 0016-5352 Number of points in the publication year: 11 pts. Percentage of participation in the publication: 50% Number of points after taking the habilitated doctor's participation into account: 5.5 pts. Impact factor in the publication year: 0 (IF), 0 (IF_{5years}) $SNIP_{2017}$ according to Scopus: 0				
Total	Number of points in the	Number of points after taking the habilitated	Impact factor in the publication year		$SNIP_{2017}$ according to Scopus
			IF	IF_{5letni}	

No.	The title of the publication				
	publication year	doctor's participation into account			
	215	142.9	9.008	8.983	6.916

The substantive participation in co-authored publications mainly consisted in defining the problem, setting the assumptions and methodology of research and formulating conclusions.

The scope characterizing the participation of co-authors was attached to the application as Appendix 8.

4.3. DISCUSSION OF THE SCIENTIFIC OBJECTIVE, APPLIED RESEARCH METHODOLOGY, THE ACHIEVED RESULTS AND METHODS OF THEIR POSSIBLE USE

4.3.1. OBJECTIVES OF RESEARCH

The scientific objective of the presented single issue series of 11 publication entitled *Failure Risk Analysis and Assessment of the Water Supply Network* is:

- analysis and assessment of failure and costs associated with the removal of water pipes failures - [publication 1, 2, 3, 4, 5, 6, 7],
- determining the proper functioning of the water supply network and the consequences of a failure of individual sections by analysing the failure risk of water pipes - [publication 1, 8, 9],
- the approach of risk indicators for the operation of the water supply network in the aspect of belonging to the critical infrastructure - [publication 9, 10],
- assessment of the safety of water supply systems based on identified threats and their possible consequences – [publication 11].

Developed research and results are both elementary and cognitive as well as the application one. These studies are the author's contribution to the development of the discipline of environmental engineering, involving the development of innovative methodologies of failure risk analysis and assessment of the water supply network. Obtained results regarding analyses and failure rates as well as costs related to removing breaks in water pipes allowed to perform multidimensional comparative analyses taking into account dependencies between received clusters, which allows planning the costs of water supply network operation. The concept of cascading failures in water supply systems, which concern the sequence of independent undesirable events, was introduced to assess the resilience of the water supply system and to make risk management decisions, e.g. during crisis situations. A method of a multicriteria decision model with the implementation of a hierarchical analysis of the process was proposed in order to enable the assessment of the failure risk of the water supply network.

The developed method may also be the element of the decision-making process regarding modernization plans. The risk assessment methodology includes the implementation of the threat assessment approach using the Bow-Tie method with the use of a risk matrix and the Layer of Protection Analysis method - LOPA, which until now has not been used in water distribution subsystems.

The purpose of the conducted research is to propose a universal methodology for assessing the failure risk of the water supply network.

4.3.2. JUSTIFICATION OF TAKING RESEARCH

Undertaken research problem meets global trends regarding the maintenance of the reliability of the water distribution subsystems. Water supply networks account for up to 90% of the assets of water supply companies[1], therefore it is important to apply failure risk analysis of water supply networks in the decision making process regarding their operation and renovation or modernization work. Risk analysis of water supply networks has a direct impact on the reliability level of water supply.

According to the Act on Collective Water Supply and Sewage Disposal[2] water supply companies are obliged to ensure continuous and reliable water supply to recipients (No. 5.1.). Regulation[5] introduces the definition of "risk assessment" as "the process of hazard identification and risk analysis based on the standard PN-EN 15975-2 in force at the time of the performed assessment "Security of water supply for consumption - Guidelines for crisis management and risk - Part 2: Risk management"; while developing the risk assessment, factors specified for the water supply area, referred to in §11 items 1, 2 and 4-9, are taken into account". On the other hand, Directive 98/83/EC of November 3, 1998 on the quality of water intended for human consumption[3] and the Water Framework Directive obliged EU member states to take all necessary measures to ensure regular monitoring of water quality and quantity in order to check whether water supplies to consumers meet the requirements of current international legal regulations. Scientific solutions aimed at ensuring the required level of reliability and consumer safety are implemented in accordance with the assumptions of Water Safety Plans (WSP)[4], which should be

[1] Kwietniewski M., Rak J.: *Reliability of water supply and sewage infrastructure in Poland.* Engineering Studies No. 67, Polish Academy of Sciences, Warsaw 2010.

[2] Act dated on the 7th June 2001 *on Collective Water Supply and Sewage Disposal* (the Official Journal Law no. 72, item 747 with subsequent amendments).

[3] Council Directive 98/83/EC of 3 November 1998 *on the quality of water intended for human consumption* (the Official Journal Law no 330, 5.12.1998).

[4] World Health Organization, 2004, *Guidelines for Drinking-water Quality,* World Health Organization, Geneva. Fourth Edition, No. 1.

based on risk analyzes and assessments. These plans are recommended by the World Health Organization (WHO), International Water Association (IWA) and the European Commission.

Legal regulations regarding safety and reliability of water distribution subsystems include the WHO guidelines and the so-called Water Framework Directive and national regulations such as the Water Law Act[5], the Act on Collective Water Supply and Sewage Disposal[6], and the Regulation of the Minister of Health on the Quality of Water Intended for Human Consumption[7]. The water distribution subsystem in accordance with the Act on Crisis Management[8] belongs to the critical infrastructure crucial for the functioning of society and the state. The improper functioning of critical infrastructure may pose a threat to human health or life, which is why it must be characterized by a high level of reliability and safety. In connection with this, the Act on Crisis Management regulates the principles of developing crisis management plans aimed at preventing crisis situations, reacting in the event of crisis situations and removing their consequences.

The safety and reliability of water distribution subsystems is considered primarily from the point of view of consumers of water intended for consumption. In this respect, the risks associated with the possibility of drinking water of inadequate quality and the lack of water supply as a result of system failure are considered. It is assumed that the basic measure of the loss of safety in the water distribution subsystems is the risk defined as the ratio of the probability of an undesirable event occurring and their consequences[9,10,11].

There are many methods in the risk analysis and assessment process. The ISO/IEC 31010: 200931[12] standard describes 28 of them. They are characterized by a different approach to risk, ranging from expert methods to methods based on undesirable event scenarios. Since the introduction of risk management elements in 2009, a decisive trend in its growth has been observed. The policy of using risk standards shows that they are a practical source of knowledge. They provide proven tools to support risk management in uncertainty. The most known certification system in the world is the quality management system according to the ISO 9001

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[5] Act dated on the 20th July 2017 – *Water Law*.

[6] Act dated on the 7th June 2001 *on Collective Water Supply and Sewage Disposal* (the Official Journal Law no. 72, item 747 with subsequent amendments).

[7] Regulation of the Minister of Health on the 7th December 2017 *on the quality of water intended for human consumption* (the Official Journal Law item 2294).

[8] Act dated on the 26th April 2007 *about crisis management* (the Official Journal Law no. 89, item 590 with subsequent amendments).

[9] Rak J.: *Risk basis in the functioning of the water supply system*. Publishing House of Rzeszow University of Technology, Rzeszow 2004.

[10] Rak J., Tchórzewska-Cieślak B.: *Risk Factors in the Operation of Water Supply Systems*. Publishing House of Rzeszow University of Technology, Rzeszow 2007.

[11] Rak J., Tchórzewska-Cieślak B.: *Methods of Risk Analysis and Assessment in the Water Supply System*. Publishing House of Rzeszow University of Technology, Rzeszow 2005.

[12] IEC/ISO 31010:2010. *Risk management – Risk assessment techniques*, International Electrotechnical Commission, Geneva.

standard[13], in the second place there is an environmental management system according to the ISO 14001 standard[14]. Another is the information security management system according to ISO 27001[15]. The concept of risk analysis and assessment belongs to the ISO 31010 standard area. According to this standard, the risk is a combination of the probability of an adverse event and related effects, as well as the impact of uncertainty on the organization's goals. The definition of risk management includes a preventive and reactionary approach to this process. Formalizing the risk management process is a structured development and application of procedures, practices, analyses, assessments, controls and risk responses.

4.3.3. DISCUSSION OF THE ACHIEVED RESULTS

Analysis and assessment of failure and costs associated with the removal of water pipes failures - [publication 1, 2, 3, 4, 5, 6, 7]

Waterworks belong to technical systems that require special operational reliability. The continuity of water supply to recipients is mainly the result of a failure-free operation of the water supply network, hence water supply companies place special emphasis on efficient removal of the resulting failures[16]. This requires maintenance crews and stock levels of parts necessary to carry out repairs. It also involves providing funds to cover the costs of repairs[17]. Ensuring the continuity of supply of tap water is one of the priorities of the operation of water supply companies, which has been sanctioned in national legislation [18]. Considering the quantitative aspect of the issue in relation to water supply networks, the failure of water pipes is of key importance for the continuity of water supply. Research of pipes failure has been the subject of numerous publications, the results of which have been presented, among others, in[16,19,20,21]. Despite the wide range of research, there is a need to continue their operation, which results mainly from continuous changes in the age and structure of water supply networks, as

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13 ISO 9001:2008. *Quality management systems – Requirements,* International Organization for Standardization, Geneva.

14 ISO 14001:2004. *Environmental management systems – Requirements with guidance for use.*

15 ISO/IEC 27001:2005. *Information technology – Security techniques – Information security management systems – Requirements,* International Organization for Standardization, Geneva.

16 Kwietniewski M., Rak J.: *Reliability of water supply and sewage infrastructure in Poland.* Engineering Studies No. 67, Polish Academy of Sciences, Warsaw 2010.

17 Rak J.: *Safe tap water. Risk management in the water supply system.* Publishing House of Rzeszow University of Technology, Rzeszow 2009.

18 Act dated on the 7th June 2001 *on Collective Water Supply and Sewage Disposal* (the Official Journal Law no. 72, item 747 with subsequent amendments).

19 Hotloś H.: *Quantitative Assessment of the Effect of Some Factors on the Parameters and Operating Costs of Water-Pipe Networks.* Wroclaw University of Technology Publishing House, Wroclaw 2007.

20 Kwietniewski M., Roman M., Kłoss-Trębaczkiewicz H.: Reliability of Water Supply and Sewage Systems. Arkady, Warsaw 1993.

21 Zimoch I.: *Reliability analysis of water-pipe networks in Cracow, Poland.* Environmental Engineering III, Eds.: Pawlowski L., Dudzinska M.R., Pawlowski A., 3rd Congress of Environmental Engineering, Lublin, 13-16.09.2009 r., s. 561-565.

these data constitute one of the main indicators for the operational policy of water supply networks. Criteria forming the basis for determining the reliability of water supply to recipients have been presented in the studies[22,23,24].

Analysis of the risk of failure of the water supply network should be carried out in the following stages:

- determination the type of water supply system,
- determination of the critical value of the indicator of the failure rate of the water supply network,
- identification of barriers reducing the causes and effects of undesirable events,
- determination of the criterion values of the failure risk of a water supply network.

In the works [publications 1, 2, 3, 5, 6] the analysis was made of data concerning failure the water supply network supplying from 20,000 up to 180,000 residents. Failure data was presented in a division to pipe type, diameter, and material. Also, the variability of the water supply network failure in time, as to assess the cycle of seasonal fluctuations on the occurrence of failures of the water supply network was shown [publications 3, 5, 6, 7].

The studies are based on the values of the following failure rates used in the analysis of the functioning of the water supply system[25]:

- failure rate $\lambda(t)$ [no. of failures$\cdot a^{-1} \cdot km^{-1}$], determined as the number of failures in time Δt by the length of the tested pipes in the time interval Δt,
- Mean Time To Repair - *MTTR* [h] describing the average time from the onset of failure to re-enable the flow of water in the damaged section of the water supply network,
- theintensity of repair $\mu(t)$ [no. of repairs$\cdot$year$(h)^{-1}$] specifies the number of failures per unit of time, it can be defined as the inverse of the average repair time,

  and indicators to determine seasonal and accidental fluctuations:
- seasonal seasonality ratio based on average one-year periods,
- the absolute level of seasonal fluctuations,
- trend indicator of the time series, determined by moving averages centred for quarters,
- additive and multiplicative seasonal variations for the fluctuation cycle for unimpeded sub-periods,
- individual one-point chain indexes.

[22] Kwietniewski M., Roman M., Kłoss-Trębaczkiewicz H.: *Reliability of Water Supply and Sewage Systems*. Arkady, Warsaw 1993.

[23] Roman M.: *Problems of reliability criteria for municipal water and sewage systems.* Conf. Proc. „Reliability of water supply and sewage systems, Publishing House PZITS Cracow, 1986, s.13-26.

[24] Wieczysty A.: *Reliability of Water and Wastewater Systems I and II*. Publishing House of Cracow University of Technology, Kraków 1990.

[25] Kwietniewski M., Roman M., Kłoss-Trębaczkiewicz H.: *Reliability of Water Supply and Sewage Systems. Arkady, Warsaw 1993.*

Risk (r) considered in the context of security in the face of a hazard may also be expressed as a function of availability index ($r = R(t)$), where the availability indicator expresses the probability with which the system will have an operational capability at time t and is defined as the dependence of average time between failures as Mean Time Between Failures *MTBF*, by the sum of MTBF sum and average time of repair *MTTR*[26,27,28].

The presented indicators may be helpful in describing the proper functioning of the water distribution subsystem, both for the operator of this system and for the recipient of water in terms of reliability and operational safety.

The average values of the failure rate index for the analysed water supply networks are [publications 2, 3, 4, 7, 8, 11]:

- for mains λ_{Mavg} = 0.54 no. of failures$\cdot a^{-1}\cdot km^{-1}$, λ_{Mmed} = 0.48 no. of failures$\cdot a^{-1}\cdot km^{-1}$,
- for distribution pipes λ_{Davg} = 0.27 no. of failures$\cdot a^{-1}\cdot km^{-1}$, λ_{Dmed} = 0.26 no. of failures$\cdot a^{-1}\cdot km^{-1}$,
- for service connections λ_{SCavg} = 0.52 no. of failures$\cdot a^{-1}\cdot km^{-1}$, λ_{Pmed} = 0.38 no. of failures$\cdot a^{-1}\cdot km^{-1}$.

Analysing the failure rate, it can be concluded that the number of failures and thus the failure rate is systematically decreasing in the considered water distribution subsystems, which in turn may be caused by renovation works of water supply pipelines in recent years and making new pipes from more durable materials that are less prone to failures. It can be noticed that the main failures characterize mains, this is most often due to the age of these pipes and the fact that they are made from cast iron and steel, which are subjected to damage more often than for example pipes from PE, which are mostly converted from old pipes. According to the work[29], the failure rates for the mains should not exceed 0.3 no. of failures$\cdot a^{-1}\cdot km^{-1}$, therefore it can be concluded that the mains are pipes requiring renovation or replacement. Distribution pipelines and service connections meet the limit values for this indicator, respectively 0.5 no. of failures$\cdot a^{-1}\cdot km^{-1}$ and 1.0 no. of failures$\cdot a^{-1}\cdot km^{-1}$. Taking into account the material structure of the considered water supply systems, the highest failure rate is characterized by water supply pipes made of grey cast iron ($\lambda_{castiron}$ = 0.779 no. of failures$\cdot a^{-1}\cdot km^{-1}$) and galvanized steel ($\lambda_{galvsteel}$ = 0.802 no. of failures$\cdot a^{-1}\cdot km^{-1}$), so for the oldest water pipes made of this material. The currently used materials for the construction of water supply networks of plastics such as PVC and PE have low values of the failure rate, respectively λ_{PVC} = 0.100 no. of failures$\cdot a^{-1}\cdot km^{-1}$ and λ_{PE} = 0.112 no. of failures$\cdot a^{-1}\cdot km^{-1}$. The increased failure rate of specific materials determines the cause of failure, therefore the highest rates were noted for failure caused by corrosion and cracks, the

[26] Kołowrocki K., Soszyńska-Budny J. *Reliability and Safety of Complex Technical Systems and Processes: Modelling – Identification – Prediction – Optimization*. Springer-Verlag London 2011.

[27] IEC 61508-4 *Functional safety of electrical/electronic/programmable electronic safety-related systems* - Part 4: *Definitions and abbreviations.*

[28] IEV 191-12-07 *Dependability and quality of service/Reliability performance measures.*

[29] Rak J.: *Fundamentals of Water Supply System Safety.* Polish Academy of Science, Lublin 2005.

median of the above-mentioned causes was respectively $\lambda_{corrosion}$ = 0.36 no. of failures·a^{-1}·km^{-1} and $\lambda_{cracking}$ = 0.26 no. of failures·a^{-1}·km^{-1}.

A tenfold increase in the failure rate was observed along with the increase in the age of the pipe in the range of 10-50 years, from $\lambda_{<10;20)}$ = 0.092 no. of failures·a^{-1}·km^{-1} to $\lambda_{<40;50)}$ = 0.94 no. of failures·a^{-1}·km^{-1}, the youngest pipes show failure rate $\lambda_{10\ years}$ = 0.24 no. of failures·a^{-1}·km^{-1} related to material defects and manufacturing errors, while the oldest pipes are characterized by failure rate of $\lambda_{\geq 50\ years}$ = 0.31 no. of failures·a^{-1}·km^{-1} and this can be explained by the high quality of workmanship and the used material.

On the basis of literature data and analyses of water network failures carried out in various water distribution subsystems, the following acceptability criteria were proposed in assessing the failure risk of water supply networks in relation to selected priority indicators, which should determine the assessment of the reliability level:

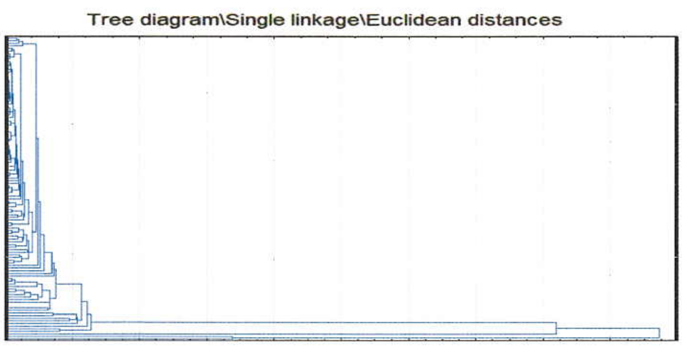
- for water supply systems supplying less than 2000 recipients:
  - failure rate: $\lambda(t)_{tolerable} \leq 0.9$ no. of failures·a^{-1}·km^{-1}, $\lambda(t)_{controlled}$ from 0.9 to 2.0 no. of failures·a^{-1}·km^{-1}, $\lambda(t)_{unacceptable} \geq 2.0$ no. of failures·a^{-1}·km^{-1},
  - average repair time: $MTTR_{tolerable} \leq 3$ h, $MTTR_{controlled}$ from 3 to 24 h, $MTTR_{nunacceptable} \geq 24$ h,
- for water supply systems supplying more than 2000 and less than 200 000 recipients:
  - failure rate: $\lambda(t)_{tolerable} \leq 0.5$ no. of failures·a^{-1}·km^{-1}, $\lambda(t)_{controlled}$ from 0.5 to 1.5 no. of failures·a^{-1}·km^{-1}, $\lambda(t)_{unacceptable} \geq 1.5$ no. of failures·a^{-1}·km^{-1},
  - average repair time: $MTTR_{tolerable} \leq 2$ h, $MTTR_{controlled}$ from 2 to 18 h, $MTTR_{unacceptable} \geq 18$ h,
- for water supply systems supplying more than 200 000 recipients:
  - failure rate: $\lambda(t)_{tolerable} \leq 0.5$ no. of failures·a^{-1}·km^{-1}, $\lambda(t)_{controlled}$ from 0.5 to 1.0 no. of failures·a^{-1}·km^{-1}, $\lambda(t)_{unacceptable} \geq 1.0$ no. of failures·a^{-1}·km^{-1},
  - average repair time: $MTTR_{tolerable} \leq 2$ h, $MTTR_{controlled}$ from 2 to 12 h, $MTTR_{unacceptable} \geq 12$ h.

The problem of failure rate is a particularly important issue in the assessment of the functioning of water distribution subsystems, where the possible consequences of undesirable events may affect the health and life of water recipients. The aspect of water quality and its continuity is of particular importance for consumers. Serious consequences entail long-term interruptions in water supply, for example by disenabling extinguishing fires, which is why it is necessary to conduct periodic analyses related to the failure of the water supply network.

In the papers [publication 2, 4] analyses the operational data of labour costs related to the repair of water pipes were presented, in the division into material and diameter of pipes of nominal diameters. The research was conducted in water distribution subsystems of medium-sized cities located in southern Poland. The research was performed on the basis of the developed failure charts filled out by the employees of the water supply company. The scope of collected information included: location, diameter, material and age of the pipes, the probable cause of damage and used equipment, materials and work time, as well as the number of the repair brigade. The effects of the accident were also determined: the number of recipients and the number of inhabitants without water, the time of interruption in water supply and the unit water consumption at that time. An important component of the costs of removing breakdowns is the labour cost, which is the product of working time and unit price of man-hour. The term repair time should be understood as the number of man-hours, that is the product of the repair time and the number of employees performing repair activities. The presented analysis showed that labour costs related to the repair of water pipes show considerable variation. It was noted that they are most dependent on the diameter of the pipe being repaired. However, even within individual diameters, they show a large discrepancy. These costs are not the result of pipe function, however, due to the connection of diameters with the pipe function, it can be stated that the lowest unit costs relate to service connections, then distribution pipes and the biggest mains. The average cost of failure amounted to 730 PLN (the level of prices in 2015). Diversification of costs for individual materials was also shown, in the case of steel, the average cost of repairs exceeded costs in the case of grey cast iron and PE. Also, a higher cost of labour was noted in the event of a failure occurring in the roadway or sidewalk.

As to compare the costs for removing failures, taking into account the costs of materials, labour, and equipment incurred for the removal of failures on different water pipes the approach of multidimensional comparative analysis was used. In order to estimate the distance between the clusters, the following applications were proposed single linkage method, complete linkage method, weighted pair-group method using arithmetic averages WPGMA and Ward's method[30] (Fig. 1). For further analysis, Ward's method was taken into account, thanks to which it was possible to create homogenous concentrations. In order to present the characteristics of the analysed failures and the related costs, the average of each cluster was determined by the *k*-means method. This method guarantees receiving clusters, which maximally differs from each other, what after grouping a large number of elements considerably increases the transparency of the obtained results.

a)



[30] Abonyi, J., Feil B.: *Cluster Analysis for Data Mining and System Identification.* Birkhauser Verlag AG, Germany 2007.

b)

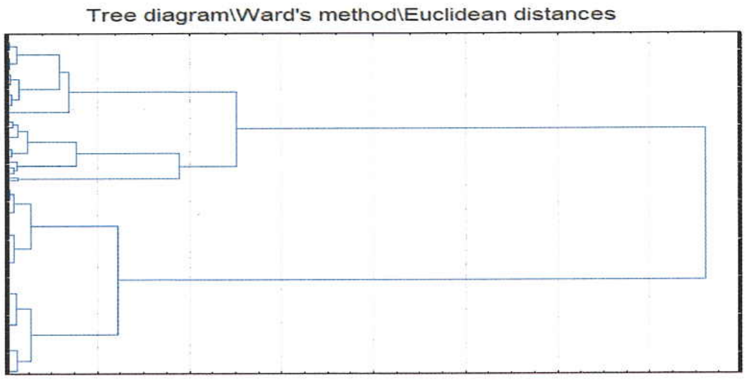
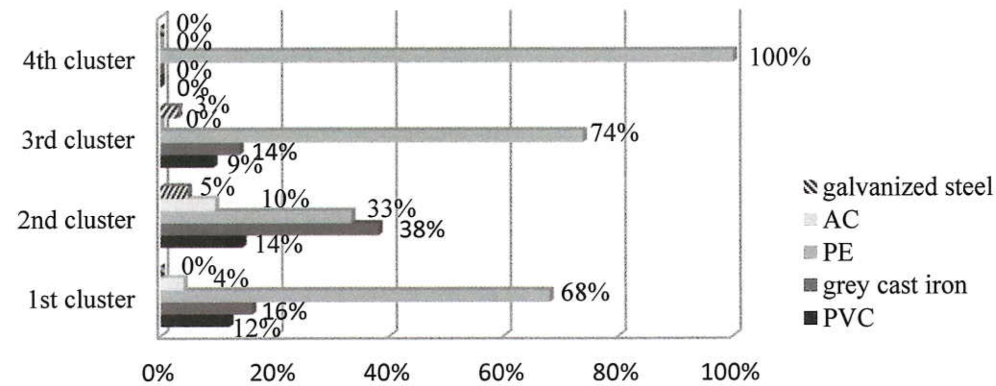


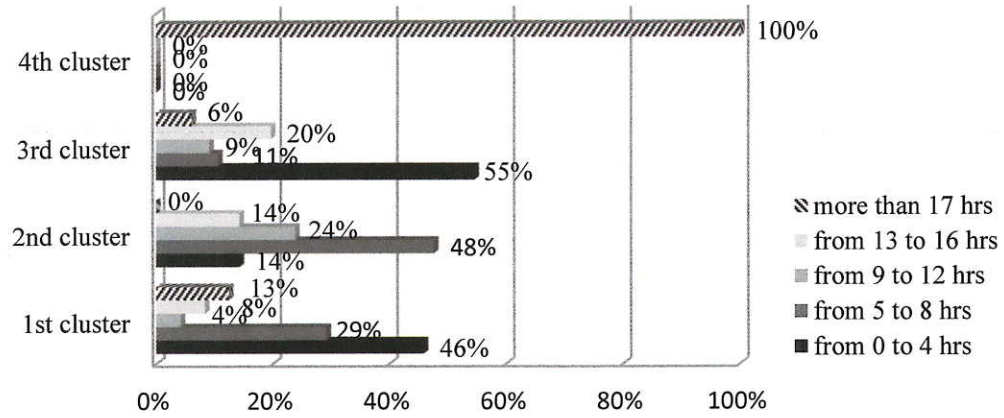
Figure 1. Tree diagram of differentiation of particular failures for the single (a) and Ward's method (b)

The aggregated costs of each cluster can be characterized as follows: 1st cluster covering 22.61% of all failures - high material cost ($\overline{x}$ = 59.83 PLN) and average labour costs and equipment for failure removal ($\overline{x}$ = 317.80 PLN), 2nd cluster covering 18.26% of all failures - high material costs ($\overline{x}$ = 59.68 PLN) and high labour and equipment cost for failure removal ($\overline{x}$ = 554.01 PLN,), 3rd cluster covering 1.74% of all failures - very high material costs ($\overline{x}$ = 82.97 PLN) and very high labour cost and equipment for failure removal ($\overline{x}$ = 1456.28 PLN) and 4th gathering 57.39% of all failures very low material costs ($\overline{x}$ = 10.07 PLN) and very low labour and equipment costs for failure removal ($\overline{x}$ = 112.16 PLN). In order to assess the impact of particular factors on the grouping of individual clusters, the characteristics presented in the figure 2 were made.

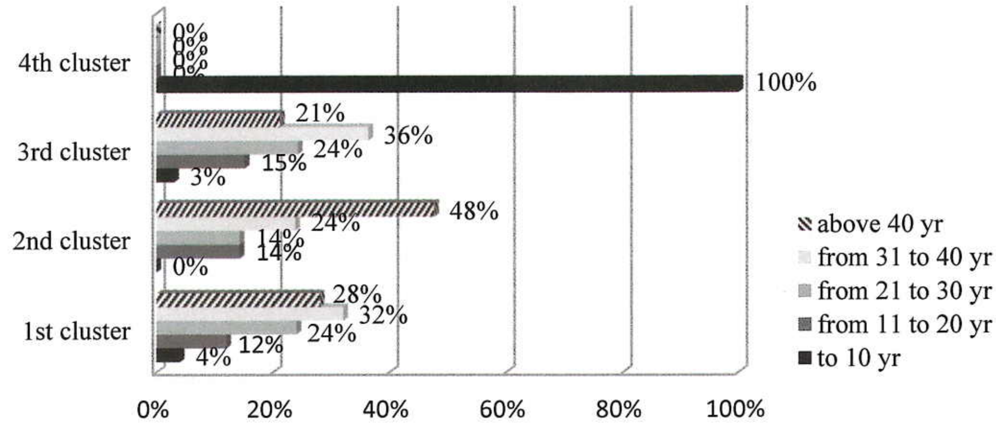
a)



b)



c)



d)

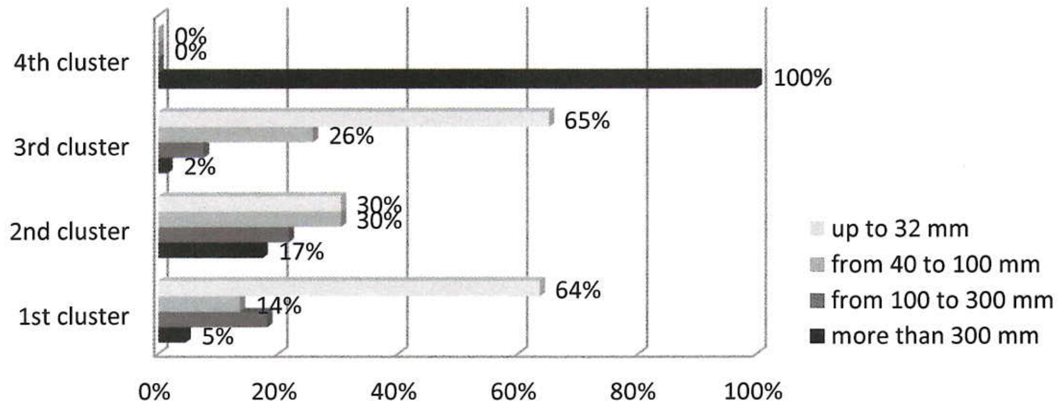


Figure 2. Characteristics of particular clusters by the k-means method, considering: a) material, b) time of failure removal, c) pipe age, d) pipe diameter.

The presented methodology with the use of multidimensional comparative analysis and the collected data may be a component of the risk of the water distribution subsystem operator. The analysis taking into account the costs of materials and equipment is used in the planning of operating costs of water supply networks.

Determining the proper functioning of the water supply network and the consequences of failure of individual sections by analysing the failure risk of water pipes - [publication 1, 8, 9]

Obecnie wymagania związane z dostawą wody wzrastają, dlatego też dostawcy wody powinni ograniczyć ryzyko związane z awariami przewodów wodociągowych, a w związku z tym z brakiem dostawy wody, bądź jej dostawę o złej jakości. W celu zapobiegania pojawiania się takich problemów należy prowadzić analizę ryzyka poprzez symulacje przewodów wodociągowych.

W pracach [publikacje 1, 8] dokonano analizy skutków stanów awaryjnych przewodów wodociągowych. Wyniki przeprowadzonej analizy pozwoliły na wyodrębnienie odcinków, których awaria w różnym stopniu wpływa na prawidłową pracę układu. Przeprowadzenie analizy wybranych odcinków pozwoliło na wyodrębnienie tych, dla których awarie mają duże znaczenie. Model opierał się na bieżącym zapotrzebowaniu na wodę wraz z jego aktualnym rozkładem. Podjęty w pracy termin ryzyka związany jest z ryzykiem wystąpienia awarii na poszczególnych przewodach sieci wodociągowej. Risk is generally defined as the expected value of the losses and can be presented by the formula[31,32]:

$$r = P \cdot C, \tag{1}$$

where:

P - the probability of failure occurrence,

C - consequences (losses, effects) of undesirable event occurrence.

The failures on the pipes cut off from water the supplied residents. In order to analyse the consequences related to the occurrence of pipe failure, and hence the extent and duration or size of water supply limitations, an updated hydraulic model was developed in Epanet 2, which maps the operation of the network. This model shows the current state of the water demand, together with the current water distribution in the analysed system supplying water for about 200 thousand residents. In this model also the cooperation of the second-degree pumping station with the expansion tanks was presented. The analysis referred to the comparison of the network working without failure for 24 hours with the operation of the network when the failure occurs. The proposed model allowed to determine to perform analysis of the operation of the water supply network. The scope of work includes compiling information about the water supply system and making the hydraulic model of the water supply network, performing the hydraulic simulation of pipeline failure, presentation and summarizing the results of the simulation. The limit values of risk have been adopted on the basis of the analysis of the operational data of the analysed water supply system. The limit value of tolerable risk was determined by multiplying

[31] Rak J., Tchórzewska-Cieślak B.: *Risk Factors in the Operation of Water Supply Systems*. Publishing House of Rzeszow University of Technology, Rzeszow 2007.

[32] Rak J.: *Risk Basis in the Functioning of the Water Supply System*. Publishing House of Rzeszow University of Technology, Rzeszow 2004.

the probability of failure falling on one segment of the distribution network and the number of residents cut off from water supply per one section of the network, respectively R = 0.085. The limit value for controlled risk has been adopted for the main network and amounted to R = 0.62. For 23% of examined pipes, the risk value exceeds the tolerable risk. The risk of the tested water supply system takes a small value because during failure of individual water pipes, water is cut off only to the recipients being supplied from those pipes, however, those values are quite a large reaching, in extreme cases, several thousand residents without a water supply. After a detailed analysis of the hydraulic model, it was found that the pressure in the nearest area does not fall enough to cause problems with water supply. A major impact on this situation has also a ring structure included in the model and oversizing of the water supply network. The performed analysis can be an important method to point out the segments of the water pipe network which should be modernized in the first place because of their major importance for the recipients. Hence the need for a particular focus on their performance, including qualifying for the reconstruction or renovation. The presented method does not cover all factors influencing the decision-making processes in the activities of the operating water pipes, an outstanding example is the earlier pipe reconstruction cables, despite satisfactory technical state technical, due to the road reconstruction. This method indicates, courses of the water supply system operator in order to achieve the best technical result in the assumed operating conditions of the system.

In order to assess the risk of propagation of pollutants in the water-pipe network, the classical definition of risk understood as the expected value of losses was applied to the relative load of pollution taken from the tap water to the human body was used [publication 9]. The method of risk estimation based on the analysis of the propagation of pollutants in the water supply network in the case of contamination of water in the treated water tank is proposed. The analysed real water network is a group water supply, supplying about 15 thousand residents. The hydraulic analysis was performed using the Epanet program based on the verified hydraulic model of the water supply network. The distribution of pollutant concentrations in the water supply network was determined over time and on its basis, the mass of pollutants collected by the statistical consumer of tap water was calculated. The type and toxicity of the contaminant and its initial concentration are of basic importance for the health risk of the consumer, but as the analysis presented shows, the relevant parameters are also the spatial configuration of the water supply network and the size of the distribution. During the simulation of a 24-hour simulation of pollution spread in the water supply network, contaminated water reached to 86.7% of water consumers, and over 30% of residents could have consumed contaminated water after only three hours from the occurrence of the contamination. The performed simulation shows how sensitive to contamination may be modern water supply systems in case of accidental contamination. Especially important is a time of contamination propagation. It results mainly from the spatial layout of the water supply network and the amount of water demand.

Indicators of the operation risk of the water supply network - [publications 9, 10]

From among a large number of values used to describe losses *C*, it is the descriptive indicators that predominate. Magnitudes for both, along with probabilities of failure and resultant losses, were presented in the form of risk weightings and matrices[33,34,35]. These methods have evolved through the introduction of more and more factors affecting losses[36], for example, exposure to threat, the number of people potentially affected by the consequences of failure, the influence of protective barriers preventing the occurrence and consequences of threats[37], and so on[38,39].

For the evaluation of losses as a result of a water pipes failure the indicator of the expected value for the water shortage was used. This indicator links the probability of failure with the resulting water shortage[40]. The total volume of water needed in the assumed balancing period was taken as the nominal daily demand Q_n.

The value capable of being defined as the measure of risk is time over which the water supply fails to meet consumer requirements. This value expresses the time for which a consumer is exposed to a water supply below acceptable standards in both quantitative and qualitative terms. The value of this indicator is expressed in terms of time (hours) of exposure of the average consumer of water each year - i.e. Substandard Supply Hours - SSH. Risk can be also described by reference to indicators used in other industries (for example in the energy industry), such as Average Short Interruption Frequency Index, Average Long Interruption Frequency Index, and others. In the case of water pipes, the range of consequences of failure can be seen in terms of expected numbers of customers without water due to a failure of the pipe. In this case, the risk indicator is the expected number of residents affected by water deficit E(INH). This indicator has some limitations arising from the fact that other groups of water consumers - mainly industry and services - are not taken into account. This disadvantage can be eliminated by expressing losses as the expected number of service connections lacking supply as a result of the consequences of pipe failures. This value does not take into account the value of water intake

[33] Rak J.: *Risk basis in the functioning of the water supply system*. Publishing House of Rzeszow University of Technology, Rzeszow 2004.

[34] Rak J., Tchórzewska-Cieślak B.: *Risk Factors in the Operation of Water Supply Systems*. Publishing House of Rzeszow University of Technology, Rzeszow 2007.

[35] Rak J., Tchórzewska-Cieślak B.: *Methods of Risk Analysis and Assessment in the Water Supply System*. Publishing House of Rzeszow University of Technology, Rzeszow 2005.

[36] Pietrucha-Urbanik K., Studziński A.: *Qualitative analysis of the failure risk of water pipes in terms of water supply safety*, 2019, Engineering Failure Analysis, Vol. 95, pp. 371-378, ISBN/ISSN: 1350-6307.

[37] Rak J.: *Fundamentals of Water Supply System Safety*. Polish Academy of Science, Lublin 2005.

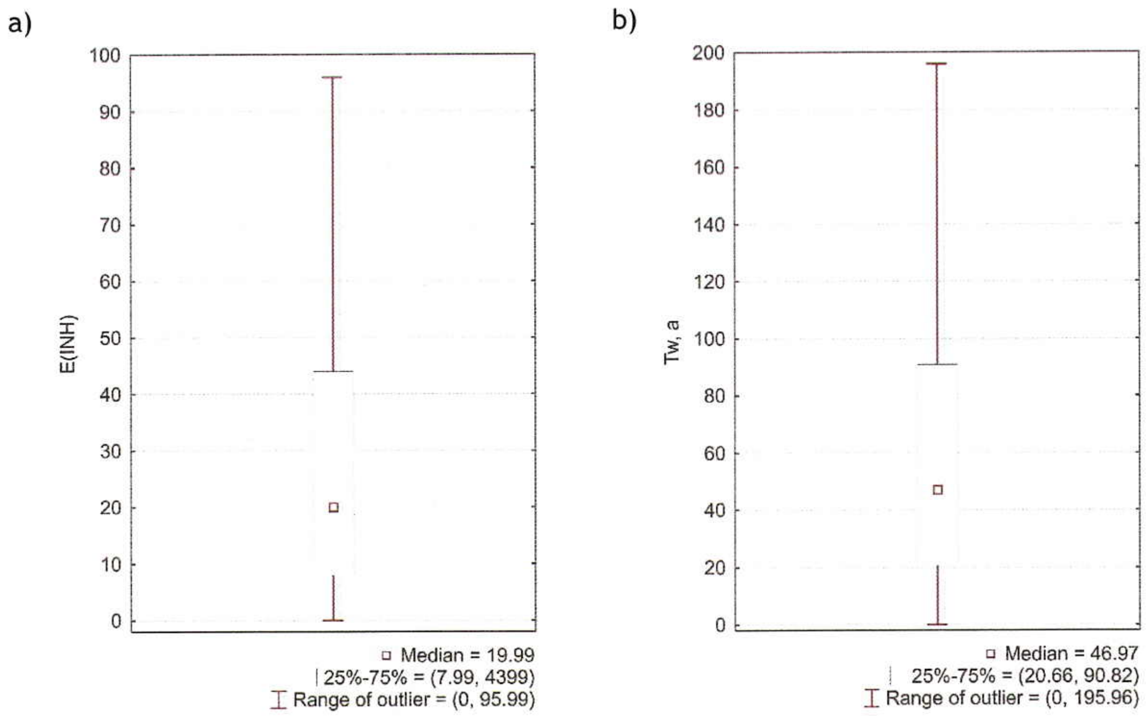
[38] Kwietniewski M, Roman M, Kłoss-Trębaczkiewicz H.: *Reliability of Water Supply and Sewage Systems*. Arkady, Warsaw 1993.

[39] Wieczysty A.: *Reliability of Municipal Water Systems*. Publishing House of Cracow University of Technology, Cracow 1993.

[40] Wieczysty A., Iwanejko R.: *Calculating required reliability level of water supply system*, 1996, Gas, Water and Sanitary Technique, No. 2, pp. 54-58.

by individual recipients, so that the obtained results may not be reliable. Therefore, as a negative effect of a failure, a universal quantity equal to the water demand for all groups of recipients, taken together as a statistical inhabitant, hereinafter referred to as an equivalent inhabitant, is introduced. This indicator allows for differentiating water recipients for both housing and other groups of institutional recipients. Although not specify the issues from a financial point of view, however, clearly evaluates the effects of the failures of pipes while maintaining the simplicity of estimation, which allows it to spread in risk management.

Estimation of the risk of water pipes was performed for one of the cities of south-eastern Poland [publication 9]. Based on the verified hydraulic model of the water supply network, simulations of closing individual pipes from exploitation were performed, the analysis allows to conclude that in the case of distribution pipes the effects of failure apply only to consumers connected directly to these sections. The results are shown in Figure 4.



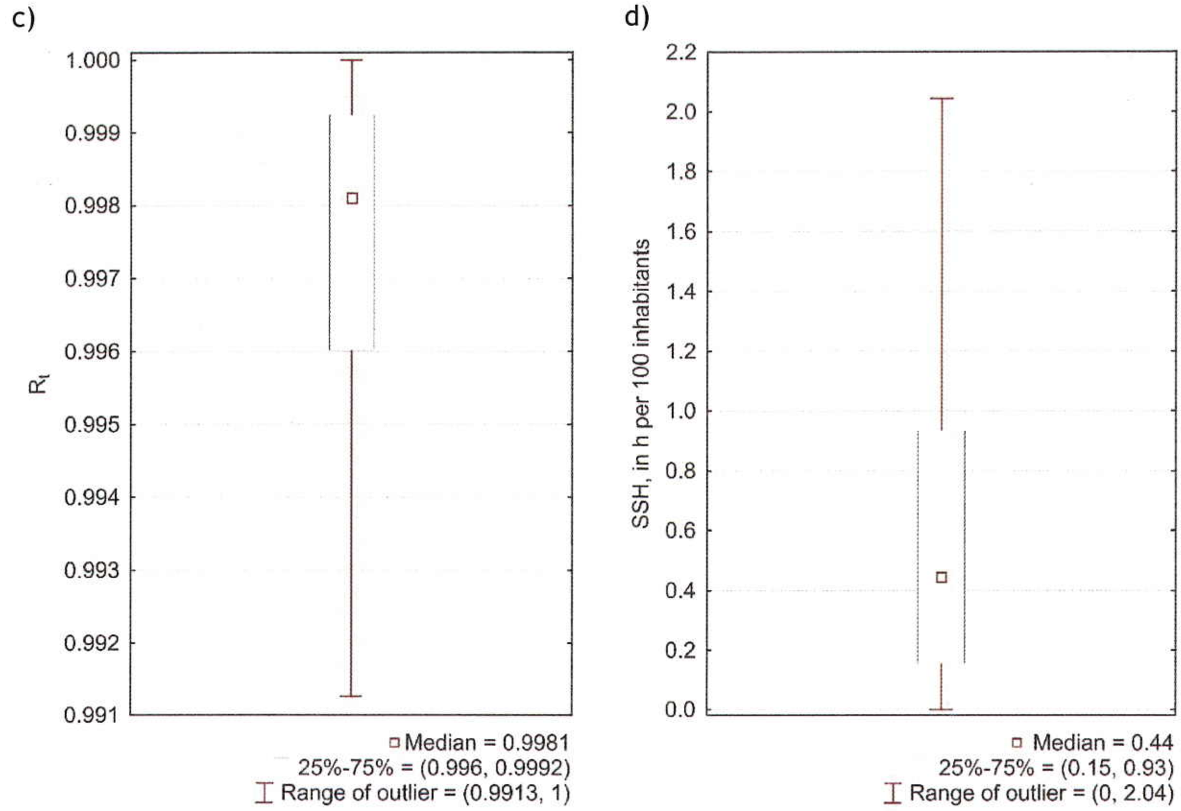


Figure 5. Summary of risk calculations for the water network: a) the expected number of residents affected by water deficit - E(INH), b) the average working time without failures - Tw, c) the risk indicator - R_t, d) Substandard Supply Hours - SSH, hour

As to express losses resulting from pipe failures the value of the expected number of residents without water allowing for numerical estimation of losses, and in particular comparing the effects of undesirable events, which may facilitate decision-making processes in a water supply company was proposed. The presented methodology is at the same time relatively simple, and the range of data necessary for risk assessment usually coincides with the values currently used in operational practice.

An effective risk management process should enable an exhaustive review and analysis of all likely events or sequences of events that may disturb the continuity of water supply. The process includes hazard identification, failure data analysis, model development, and consequence analysis, which leads to risk quantification using dynamic models to describe susceptibility to undesirable events and other processes, e.g. aging of water supply materials. Risk management using dynamic sequence modelling of independent events to assess the resilience of the water supply system is presented in the work [publication 10], which introduced the concept of cascading failures in water supply systems. The sequence of undesirable events was created as a result of a single emergency event caused by corrosion of the water pipe (E_1), after which subsequent events appear (pipe break - E_2, failure to localise the broken pipe - E_3, failure to repair/replace and to restore the water supply services - E_4) is described by stochastic Poisson processes.

The probability of occurrence of the sequence of undesirable events $P_{n+1}(t)$ is described as:

$$\Delta P_{n+1}(t) = P_n(t).e^{-\lambda_{n+1}t}.\lambda_{n+1}\Delta t, \quad (2)$$

where:

$\Delta P_{n+1}(t)$ - the infinitesimal occurrence probability of the n^{th} event within the infinitesimal period "Δt" in the neighborhood of "t",

$P_n(t)$ - the occurrence probability of the n-first events within the interval "t",

$e^{-\lambda_{n+1}t}$ - the non-occurrence probability of the $(n+1)^{th}$ within the interval "t",

$\lambda_{n+1}\Delta t$ - the infinitesimal occurrence probability of the $(n+1)^{th}$ within the infinitesimal period "Δt" in the neighborhood of "t".

The occurrence probability $P_4(T)$, within an interval T, of the sequences is described by:

$$P_4(T) = \int_0^T e^{-\lambda_1\xi_1}\lambda_1 d\xi_1 \int_{\xi_1}^T e^{-\lambda_2\xi_2}\lambda_2 d\xi_2 \ldots \int_{\xi_3}^T e^{-\lambda_4\xi_4}\lambda_4 d\xi_4, \quad (3)$$

The incremental loss of resilience, Δ_{res} is given by:

$$\Delta_{res} = [P_n^*(\Delta T) - P_n(\Delta T)] \cdot \Delta T, \quad (4)$$

where, $P_n^*(\Delta T)$ and $P_n(\Delta T)$ are the stressed and the unstressed sequence occurrence probabilities. The recovery rate $\lambda^*(t)$ in a given time interval corresponding to a sequence of undesirable events is described as a function of probability density.

The determined probabilities of particular events and vulnerabilities are presented in Tables 1-3 and in Figure 3.

Table 1. Occurrence rates and vulnerability data used in the study case.

List of sequential events	Unstressed Rate (/h)	Vulnerability factor	Stressed Rate (/h)
E_1	5.00E - 5	0.0	5.00E - 5
E_2	4.00E - 4	2.0	1.20E - 3
E_3	4.17E - 2	- 0.8	8.34E - 3
E_4	4.17E - 2	- 0.9	4.17E - 3

Table 2. Incremental loss of resilience in water systems.

No	T_1 - T_2	$P_n(\Delta T)$	$P_n^*(\Delta T)$	ΔT (h)	$P_n^*(\Delta T) - P_n(\Delta T)$	Δ_{res}	$P_n^*(T_2) - P_n^*(T_1)$
1	0 - 24 h	1.22E - 5	2.28E - 6	24	~- 1.0E - 5	– 2.4E - 5	2.2E - 6
2	24 - 72 h	9.66E - 5	1.17E - 4	48	~- 2.0E - 5	6.9E - 4	1.1E - 4
3	3 - 7 d	1.34E - 4	1.48E - 3	96	1.35E - 3	1.5E - 1	1.3E - 3
4	1 - 3 week	1.35E - 4	1.05E - 2	336	1.04E - 2	3.4	9.5E - 3
5	3 - 53 week	1.35E - 4	1.56E - 2	8400	1.55E - 2	130	4.9E - 3

Table 3. The likelihood of the WSS recovery as a function of time-intervals.

No	λ*(t)	Description	Unstressed	Stressed	The recovery under stressing conditions
1	$> 10^{-1}$	Very likely	< 30 h	< 30 h	Is almost similar to the unstressed situation
2	$> 10^{-2}$	Likely	30÷84 h	30÷192 h	Takes longer time at similar likelihood
3	$> 10^{-4}$	Unlikely	30÷192 h	192÷1100 h	Longer time at similar likelihood but by so far later
4	$> 10^{-6}$	Most unlikely	192÷290 h	1100÷2000 h	Time-scale is irrelevant for crisis management
5	$> 10^{-6}$	Impossible	> 290 h	> 2000 h	Time-scale is irrelevant for crisis management

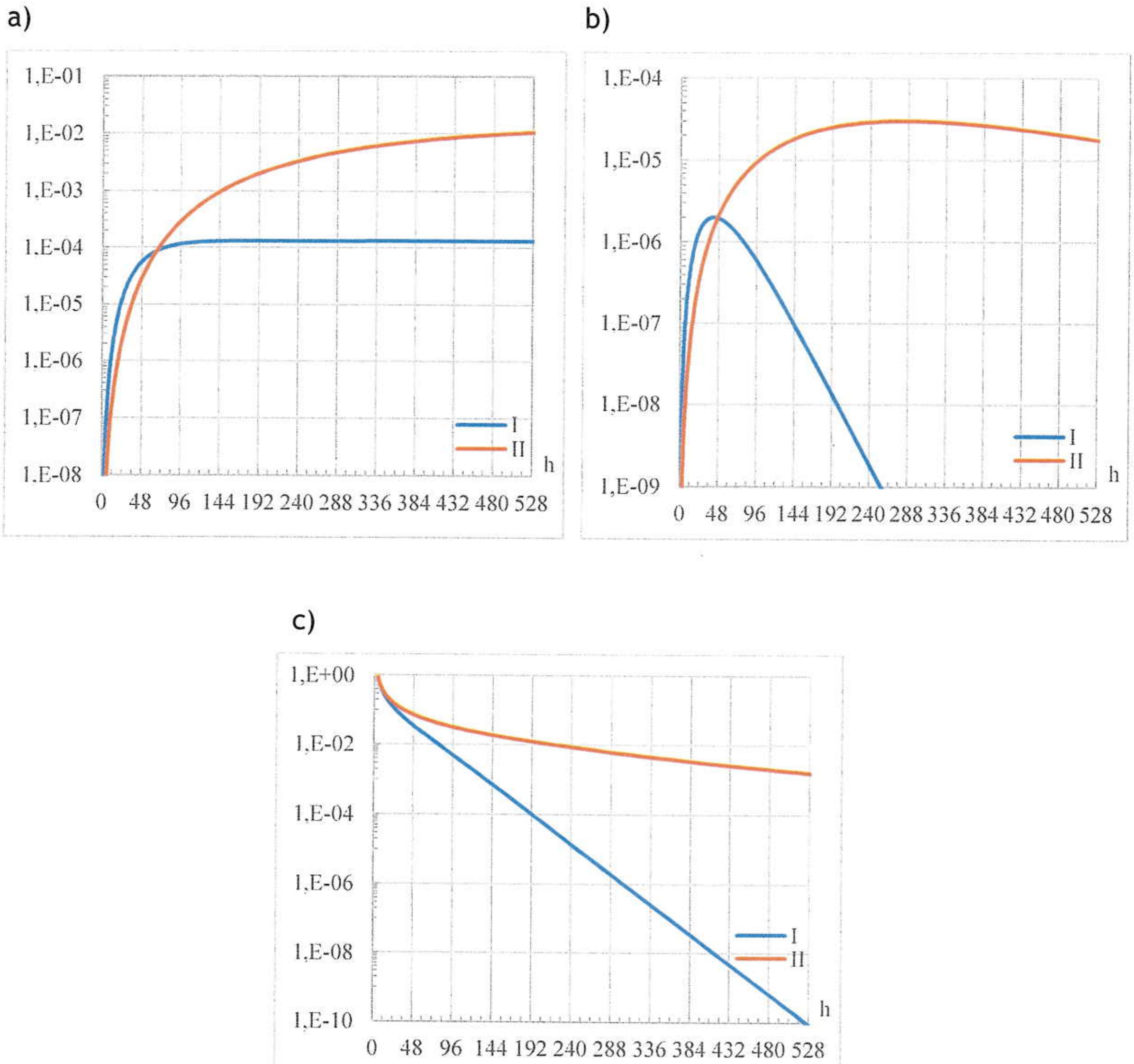


Figure 3. Recovery probability time-profile (a), Recovery probability density function time-profile (b), recovery rate time-profile (c), where: I - unstressed, II - stressed conditions.

The proposed concept of estimating the resilience of the water supply system and the sequence of cascading undesirable events may be helpful in making decisions regarding crisis management.

The approach of a Modified Multicriteria Decision Model in the assessment of the failure risk of water pipes - [publication 7]

Modified Multi-Criteria Decision Analysis (mMCDA) entails a choice of criteria influencing the risk of failure in a water distribution network (WDN), and the future occurrence thereof. The method suggested is based on risk-criteria grouping as regards failure in a WDN, with assessment then carried out by reference to determined points values under the Analytic Hierarchy Process method[41,42]. It was assumed that risk means a measure by which to assess a hazard or threat resulting either from probable events beyond our control or from the possible consequences of a decision, the appropriate risk measure is calculated using Equation 5.

$$r(A) = \sum_{j=1}^{m} w_j \cdot F_j(A), \quad (5)$$

where:

$r(A)$ - additive risk value,

w_j - the point weight for each subcategory criterion j relating to design, performance or operation, or social or financial environment or surroundings, where $j = \{1, 2, ..., m\}$

F_j - category preference for alternatives.

Part of the criteria taken to assess the failure risk of water pipes are presented in the table 4[43].

Table 4. Evaluation criteria weights - part of the criteria.

<table>
<tr><th colspan="2">No.</th><th colspan="3">Categories and Subcategories of Criteria</th><th>Point Weighting of Subcategories</th></tr>
<tr><td>1</td><td>2</td><td>3</td><td colspan="2">4</td><td>5</td></tr>
<tr><td>I</td><td>...</td><td>Design</td><td>...</td><td>...</td><td>...</td></tr>
<tr><td>II</td><td>...</td><td>Performance</td><td>...</td><td>...</td><td>...</td></tr>
<tr><td>III</td><td>IIIa)</td><td rowspan="8">Operation</td><td rowspan="3">type of WDN according to higher priority to repair</td><td>service connections,</td><td>1</td></tr>
<tr><td></td><td>IIIb)</td><td>distribution network,</td><td>2</td></tr>
<tr><td></td><td>IIIc)</td><td>mains,</td><td>3</td></tr>
<tr><td></td><td>IIId)</td><td rowspan="3">failure rate, λ</td><td>to 0.5 no.of failures · km⁻¹·year⁻¹,</td><td>1</td></tr>
<tr><td></td><td>IIIe)</td><td>from 0.5 no.of failures · km⁻¹·year⁻¹ to 1.0 no.of failures · km⁻¹·year⁻¹,</td><td>2</td></tr>
<tr><td></td><td>IIIf)</td><td>> 1.0 no.of failures · km⁻¹·year⁻¹,</td><td>3</td></tr>
<tr><td></td><td>IIIg)</td><td rowspan="2">dynamic loads, including difficulty of repairs in area in</td><td>pipeline in non-urbanized area,</td><td>1</td></tr>
<tr><td></td><td>IIIh)</td><td>pipeline in pedestrian traffic,</td><td>2</td></tr>
</table>

[41] Saaty, L.T. *A scaling method for priorities in hierarchical structures*. Journal of Mathematical Psychology 1977, Vol. 15, pp. 234–281.

[42] Saaty, L.T. *The Analytic Hierarchy Process*. McGraw-Hill: New York 1980.

[43] Pietrucha-Urbanik K., Tchórzewska-Cieślak B. *Approaches to Failure Risk Analysis of the Water Distribution Network with regard to the Safety of Consumers*, 2018, Water, No. 10(11), 1679. ISBN/ISSN: 2073-4441.

No.		Categories and Subcategories of Criteria			Point Weighting of Subcategories
1	2	3	4		5
	IIIi)		which a network is situated	pipeline in street,	3
	IIIj)		WDN age	to 20 years,	1
	IIIk)			from 20 to 50 years,	2
	IIIl)			above 50 years,	3
	IIIm)		WDN material	plastics,	1
	IIIn)			steel,	2
	IIIo)			grey cast iron,	3
IV	IVa)	Social	nuisance resulting from road occupation and green area	pipeline in non-urbanized area,	1
	IVb)			pipeline in pedestrian traffic,	2
	IVc)			pipeline in street,	3
V	....	Financial	...	...	...
VI	VIa)	Environment and surroundings	hydrogeological conditions	good,	1
	VIb)			average,	2
	VIc)			poor,	3
	VId)		density of underground infrastructure in the vicinity of the network	low,	1
	VIe)			average,	2
	VIf)			high.	3

For the considered situation presented in [publication 7], the following parameter of validity ratings were obtained (Fig. 5), not violating the principles of preferences constancy for the following parameters: the principal eigenvalue λ_{max} = 6.3071, Consistency Index CI = 0.0614, Random Index RI = 1.25, and Consistency Ratio CR = 00491.

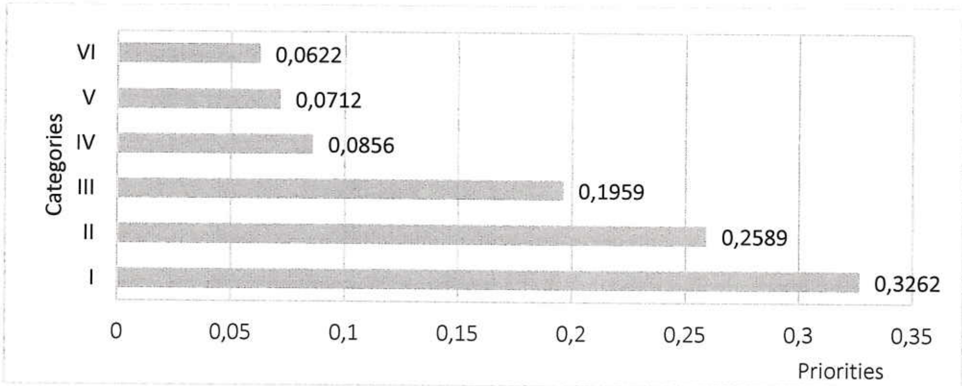


Figure 4. Evaluation of the priorities of individual criteria.

For the considered method a three-step scale to obtain the additive value of a risk category was adopted, risk assessment thus being provided for via implementation of AHP in line with a scale comprising tolerable risk [2.56÷3.06), controlled risk [3.06÷6.02) and unacceptable risk [6.02÷7.701]. The proposed scale was based on the opinions of experts, who on the basis of their knowledge, experience and data in literature concerning risk categories assessment. Assessment of the additive value of risk obtained supports the taking of decisions that relate to the operation or modernization of the system. Should a value indicating tolerable risk be obtained, no extra actions are required and the system is running in a proper and reliable way, with no preventive actions in the system needed either. Controlled risk means that the system is permitted to function but under the condition that modernization or renovation will commence. If an unacceptable level is found to have arisen, an immediate undertaking should be given, to the effect that the additive value of the risk category will be reduced. It should be noted that the consequences of failure to the water distribution subsystem are what cause periodic breaks in the delivery of water supply that is anyway of inadequate quality and quantity. Analysis of the risk of failure can contribute to the reduction of failures and their consequences.

Safety assessment of water distribution subsystems based on identified threats and their possible consequences - [publication 11]

In work [publication 11] the use of the Bow-Tie method for assessing and analysing the safety of water distribution subsystems has been proposed. In Poland, this method has not yet had practical applications in the field of water supply. The assumptions of the new methodology of safety analysis for the identified threats and their possible consequences are presented, which takes into account different scenarios of emergency situations related to the operation of water distribution subsystems. The Bow-Tie method can be used in both qualitative and quantitative terms. From a theoretical point of view, theBow-Tie method is a combination of Fault Tree Analysis - FTA and Event Tree Analysis - ETA including elements of risk control measures model[44,45,46]. In an orderly manner, information on risks and controls as well as quantitative (numerical) estimation of the effects of undesirable events are presented. The basis for determining the risk criteria was the adoption of acceptable risk criteria.

In the European Union there are different approaches to the adoption of acceptable risk criteria, for example:

- France, implementation of acceptable criteria for group risk, which were presented in the form of a matrix depending on the number of exposed people, e.g. disastrous consequences of more than 1,000 exposed people, with a low probability of occurrence 10^{-5}, [47],

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[44] Reason, J. *Human error: models and management*. British Medical Journal. Vol. 320 (7237), 2000, pp. 768–770.
[45] Kacprzak, P., Kosmowski, K.T. 2009. *Human factors in the layer of protection analysis with emphasis on alarm system management*. Conf. Proc. ESREL, Prague 2009, Reliability, Risk and Safety - Theory and Applications (ed. By Radim Bris, Carlos Guides' Soares, Sebastián Martorell), CRC Press.
[46] IEC 61508:1998. *Functional Safety of Electrical/Electronic/ Programmable Electronic Safety-Related Systems*. Parts 1-7. International Electrotechnical Commission, Geneva, Switzerland.
[47] European Commission. *Le plan de prevention des risques technologiques* (*PPRT*), Guide méthodologique, Ministère de l'Écologie, du Développement et de l'Aménagement Durables. Overview of roadmaps in selected member states, 2007.

- Great Britain, with regard to individual risk, the lower limit is 10^{-6}, while $0.3 \cdot 10^{-6}$ for particularly vulnerable people (eg. elderly, people susceptible to exposure, schools), the upper limit for passive risk eg. for employees in nearby facilities 10^{-5} in accordance with the recommendations of the Health and Safety Executive - HSE[48,49]. The risk admissibility framework developed by HSE has been adopted by other European countries, among others the Netherlands,
- Germany, guidelines are given in the work[50] and the Seveso II Directive was taken into account, determination of consequences based on detailed assumptions, or guidelines for a given activity (eg. threshold for thermal radiation 1.6kW/m^2).

The analysis of the consequences accompanying the occurrence of an undesirable event using the Bow-Tie method was performed through the use of a risk matrix and the LOPA method. The first stage of the security analysis was the identification of threats and their possible consequences, then defining the barriers preventing the emergence of threats, along with determining the degree of their effectiveness. The development of the sequence of events includes the impact of safety barriers, the aim of which is to prevent or limit the effects of the initiating event.

Figure 6 shows an example of a structured representation of the occurrence of an adverse event associated with poor quality of tap water or its absence in the water distribution subsystem. Frequency and nuisance scales of undesirable events as 5-degree events are presented in Table 5.

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[48] UK Health and Safety Executive. *Proposals for revised policies to address societal risk around onshore non-nuclear major hazard installations*, Consultative Document CD112, 2007.

[49] UK Health and Safety Executive, *Risk criteria for land-use planning in the vicinity of major industrial hazards*, 1989.

[50] UK SFK/TAA-GS-1: *Störfall-Kommission technischer Ausschuss für Anlagensicherheit, Leitfaden.* Empfehlungen für Abstände zwischen Betriebsbereichen nach der Störfall-Verordnung und schutzbedürftigen Gebieten im Rahmen der Bauleitplanung - Umsetzung § 50 BImSchG.

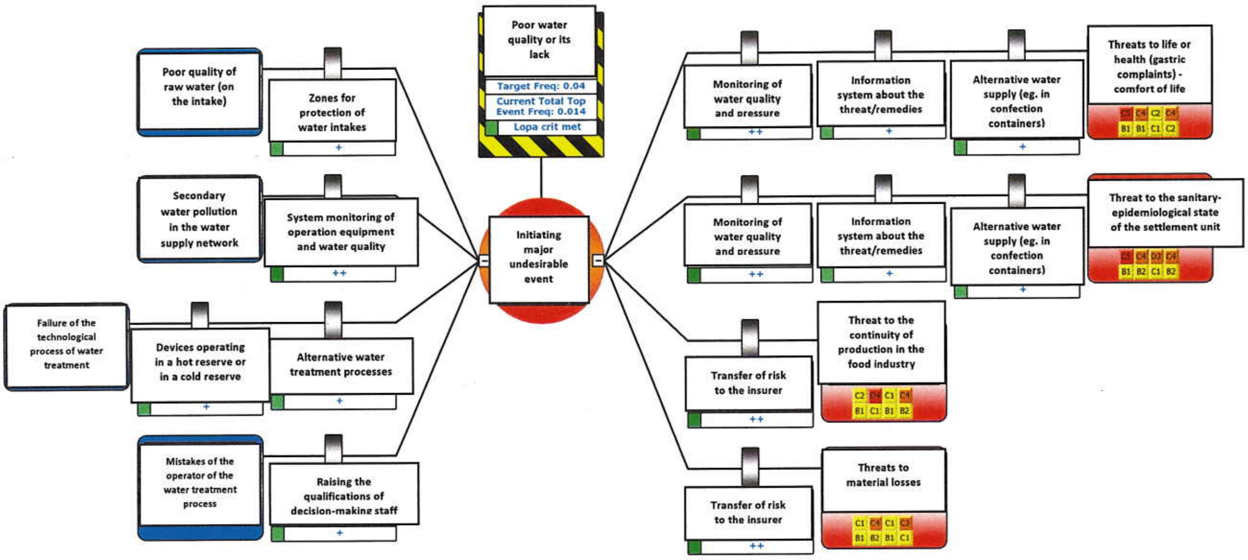

Figure 5. Application of the Bow-Tie method for the undesirable event in the water distribution subsystem related to the appearance of poor quality of tap water or its lack.

Table 5. Risk matrix.

Specification						Probability				
						Very unlikely	Unlikely	Quite likely	Probable	Very likely
Consequences	1. Human losses	2. Assets of the company	3. Environment	4. Reputation	No.	A	B	C	D	E
	Lack	Without influence	Without influence	Without influence	1	A1	B1	C1	D1	E1
	Gastric complaints	Up to 2% of the company's income	Low impact, restitution time below 1 year, restitution cost below 10,000 PLN	Negligible Local interaction	2	A2	B2	C2	D2	E2
	Required medical assistance	Up to 5% of the company's income	Local, restitution time over 1 year, the cost of restitution over 10,000 PLN	Significant but limited effect National impact	3	A3	B3	C3	D3	E3
	Hospitalization required	Up to 20% of the company's income	Large, restitution time over 10 years, the cost of restitution above 100,000 PLN	Key National impact	4	A4	B4	C4	D4	E4
	Fatal descent	Over 20% of the company's income	Very large, effects at the global or national level, restitution time over 10 years	Critical International influence	5	A5	B5	C5	D5	E5

Description: - tolerable risk, - controlled risk, - unacceptable risk

In order to evaluate the effectiveness of existing protections in the quantitative aspect in combination with the Bow-Tie method, the Layer of Protection Analysis method - LOPA was used.

The following stages of the analysis of the security layers were performed:

- determination and analysis of threats,

- identification of the initiating event and the frequency of occurrence,
- identification of the probability of damage by the probability that the technical safety system will not perform its function if necessary Probability of Failure on Demand - PFD,
- estimation and assessment of the determined frequency of occurrence of undesirable events in the aspect of acceptability, from the dependence:

$$f_i^p = f_i^k x \prod_{j=1}^{J} PFD_{il}, \tag{6}$$

where f_i^p this is the frequency of the occurrence of the i-th undesirable event and f_i^k is the occurrence frequency of the k-th of initiating undesirable events and PFD_{il} this is the probability of not performing the function by the l-th barrier.

The risk for an exemplary emergency situation appearing in the water distribution subsystem caused by secondary water pollution in the water supply network was determined on the basis of the data analysis, resulting in the frequency of occurrence of an undesirable event equal to 0.005 and the frequency of consequences for a given undesirable event 2E-08, which does not exceed the accepted acceptable frequency of consequences of the LOPA level (adopted on the basis of the British guidelines Health and Safety Executive HSE), in highly developed countries, voluntary exposure to health risks 10^{-5}), which confirms that the assumed barriers ensure the effectiveness of the water supply system in terms of the occurrence of an undesirable event in this system.

The developed method of analysis and assessment of the relationship between emerging threats and security barriers applied enables gradation of the nuisance in the form of impact classification and can be used to determine possible or additional safety barriers, which allows ensuring continuity of water supply through the water distribution subsystem.

4.3.4. ACHIEVEMENTS RESULTING FROM THE PERFORMED RESEARCH

The purpose of the conducted research was to develop a universal methodology for analysis and assessment of the risk of failure of the water supply network. The water distribution subsystem is one of the basic technical sub-systems belonging to the underground infrastructure, which is a priority for the life of the population, especially in urban agglomerations. Belonging to critical infrastructure is subject to special protection both in terms of ensuring the safety and reliability of the functioning of water supplies to recipients.

The most important scientific achievements resulting from the conducted research in the field of analysis and risk assessment of the water supply network include:

- proposition of using multidimensional comparative analyses to analyse and assess the failure rates and costs related to removing water supply failures, which may be a risk component of the water distribution subsystem operator, as well as may be used in planning the operation costs of water supply networks and allow decision support in the scope assessing the economic effectiveness of their operation,

- development of a multicriteria decision-making method with the implementation of hierarchical process analysis in order to enable the assessment of the risk of failure for the water supply network,
- developing a methodology for analysing and assessing the risk of a water supply network with the use of water supply network operational risk indicators, which will allow a reliable assessment of the functioning and may be the basis for a series of actions in the field of exploitation policy of the collective water supply system,
- introduction of the concept of cascading failures in water supply systems, which concern the sequence of independent adverse events, in order to make risk management decisions,
- implementation of the risk assessment approach using the Bow-Tie method with the use of a risk matrix and LOPA method, which may be a tool supporting operators in increasing the level of reliability and can be used to eliminate system weaknesses and reduce the probability of undesirable events,
- the proposed risk analysis and assessment methodology, based on operating data and expert knowledge, may be the basis for a comprehensive risk management program, which is part of the WHO's water safety plans, taking into account the need for modern standards regarding the safety and reliability of drinking water supplies,
- developed methods, as well as the results of the analysis will be able to be used in further studies of water distribution subsystems for their reliability and safety, in order to protect consumers of water and sustainable management of water supply systems.

The possibility of using the results

Application in the analysis and risk assessment of water supply networks.

Directions for further research

Further research should concern the introduction of a comprehensive methodology of analysis and assessment of failure risk of water supply networks for small, medium and large water supply systems, including modern IT techniques and multi-criteria decision support software, in order to make decisions on prioritizing renewal of water pipes. It also seems necessary to indicate for the discussion the criterial values in the scope of the effective functioning of the water distribution subsystem. The adoption of such values is a difficult task and should be based on many years of research and experience of experts in the reliability of the operation of water distribution subsystems.

The development of standards for effective exploitation and previous considerations form the basis for applying the solutions in water supply practice and will be the basis for managing the renewal of the water supply network.

The proposals are aimed at the pilot application of the program for selected waterworks, to confirm the conclusions resulting from the work, which will allow for proper management of the water distribution subsystem.

5. THE REVIEW OF THE OTHER RESEARCH ACHIEVEMENTS

5.1. BEFORE BEING GRANTED THE DEGREE OF A PHD

On March 21, 2011, I opened a PhD at the Faculty of Civil and Environmental Engineering at the Białystok University of Technology. The doctoral thesis advisor was appointed prof. Janusz Rak, DSc, PhD, Eng. The subject of my doctoral dissertation was as follows: *Methodology for determining the guarantee in collective water supply systems.*

My research during this period focused primarily on developing a methodology that could be used to describe the functioning of collective water supply systems (CWSS) with the use of a guarantee. The main objective of the research was to develop a model guarantee project covering the terms of water supply and guidelines for its conclusion. In my work, I conducted a survey of consumer opinions on expectations related to the guarantee of supply of drinking water. To assess the differentiation of the level of services provided in CWSS, I used the Multidimensional Comparative Analysis (MCA) method and implemented consumer indicators that set water supply standards. I have set the quality standards for the level of water supply services. I used the Fuzzy Set Theory (FST) to assess the risk associated with failure to keep the terms of the guarantee. I have developed methods for determining the guaranteed degree of accessibility of water supply services. The material obtained from operational tests conducted at the waterworks company in Rzeszow allowed for the designation of a guarantee on the example of the collective water supply system of the city of Rzeszow, and to propose a methodology for concluding a guarantee contract.

I defended my doctoral dissertation[51] on March 16, 2014 at the Faculty of Civil and Environmental Engineering at the Bialystok University of Technology and obtained a PhD degree in technical sciences in the field of environmental engineering, Council of the Faculty of Civil Engineering and Environmental Engineering at Bialystok University of Technology, defended thesis with distinction (reviewers: DSc, PhD, Eng. Dariusz Kowalski, professor at the Lublin University of Technology and Prof. Rafał Miłaszewski, DSc, PhD, Eng. - Bialystok University of Technology).

Balneology and balneotechnique

My scientific interests have also been extended to issues related to balneology and balneotherapy (spa engineering) as well as the analysis and use of mineral waters. The result of

[51] Pietrucha-Urbanik K.: *Methodology for Determining the Guarantee in Collective Water Supply Systems.* Bialystok University of Technology, the Faculty of Civil and Environmental Engineering, Bialystok 2014.

research in this area were publications on issues related to balneology, balneotherapy, spa engineering, and environmental values[52]. In the publication entitled *Approach to Analyse the State of Health Resorts Base in Podkarpackie Province*[53] on the basis of the collected material and operational data concerning the functioning of the Podkarpacie health resorts, the characteristics of spas in terms of landscape values, spa protection zones, therapeutic treatments, accommodation and service facilities were analysed, and the chemical composition of mineral and therapeutic waters occurring in the above-mentioned spas was analysed.

In the study entitled *New-old Health Resort Opportunities in the Podkarpackie Province*[54] an assessment of potential locations of the Podkarpacie region was presented in terms of the possibility of using the spa qualities and qualitative analysis of waters was made in the aspect of the possibility of spa activities renewal in these locations. Continuation of this subject is publication *Impact of water and sewage management on the assessment of tourist attractiveness of the commune*[55] published in the monograph *Water and sewage management in the Carpathians and the Carpathian Foothills and its impact on increasing the tourist attractiveness of the region*, resulting from the speech at the 9th International Ecological Conference in Brzozow. To estimate the tourist attractiveness in terms of water and sewage management, the use of a three-parameter matrix was proposed, taking into account the percentage share of treated wastewater, the percentage of wastewater treatment and the sanitary equipment class of households.

Reference was also made to balneology in Western Ukraine, making the characteristics of selected health resorts of western Ukraine, as well as the analysis of the physicochemical composition of mineral water spas in the considered Western Ukraine. In turn, in the *Journal of Scientific Papers of Rzeszow University of Technology. Civil and Environmental Engineering* publication entitled *Analysis of the composition of selected bottled mineral waters occurring in the European Market*[56] was published, in which the physicochemical composition of selected bottled mineral waters appearing on the European market was made and the hierarchy of linear

[52] *Pietrucha-Urbanik K.: Multidimensional analysis of the diversity of selected bottled mineral waters present on the European market. 2012, Journal of Scientific Papers of Rzeszow University of Technology. Civil and Environmental Engineering, No. 4, Vol. 59, pp. 83-91, ISBN/ISSN: 0209-2646.*

[53] *Pietrucha-Urbanik K., Skowrońska D.: Approach to Analyse the State of Health Resorts Base in Podkarpackie Province, Czasopismo Inżynierii Lądowej, Środowiska i Architektury Journal of Civil Engineering, Environment and Architecture JCEEA, Vol. XXXIV, No. 64 (4/I/17), October-December 2017, pp. 425-434.*

[54] *Rak J., Pietrucha-Urbanik K.: New-old Health Resort Opportunities in the Podkarpackie Province [in:] Ecological and tourist values of the northern part of the Carpathian Euroregion (ed. prof. J. Raka), 2010, Brzozow: Regional Adama Fastnacht Museum, in Brzozow, pp. 293-301, ISBN/ISSN: 978-83-86801-49-7.*

[55] *Rak J., Pietrucha-Urbanik K.: Impact of water and sewage management on the assessment of tourist attractiveness of the commune. [in:] Water and sewage management in the Carpathians and the Carpathian Foothills and its impact on increasing the tourist attractiveness of the region (ed. prof. J. Raka), Brzozow: Regional Adama Fastnacht Museum, in Brzozow, Vol. 3, pp. 177-185, 2009, ISBN/ISSN: 978-83-86801-42-8.*

[56] Pietrucha-Urbanik K.: *Analysis of the composition of selected bottled mineral waters present on the European market.* 2012, *Journal of Scientific Papers of Rzeszow University of Technology. Civil and Environmental Engineering*, No. 4, Vol. 59, pp.71-82, ISBN/ISSN: 0209-2646.

ordering was presented, according to mineral water components, the analysis covered 1030 mineral water.

In the work *Balneotechnique. Qualities of health resorts*[57] analysis of the concept of solutions for treatment units and technical balneological installations, including the installation of mineral and mud water was analysed. Analysis of the failure of sources and installations of mineral waters as well as an exemplary analysis of the reliability of balneological installations through the implementation of the fault and the event tree method was presented. Issues related to the control of the quality of natural mineral waters in the aspect of health security were analysed according to the system's methodology of Hazard Analysis Critical Control Points - HACCP, aimed at ensuring the safety of mineral waters by identifying and assessing threats from the point of view of health quality and the risk of hazards during the course of all stages of production and trade in mineral waters.

5.2. AFTER BEING GRANTED THE DEGREE OF A PHD

After obtaining the degree of doctor of technical sciences, I was employed as an assistant professor and since 2014 I have been working in the Department of Water Supply and Sewage Systems at the Faculty of Civil and Environmental Engineering and Architecture of Rzeszow University of Technology and I have undertaken scientific research related to the safety and reliability of water distribution subsystems.

The undertaken issue in research work also concerns on the analysis and safety assessment of the quality of tap water in terms of risk analysis, loss of biological and chemical stability of water. The main achievement of my work in this area is the publication in 2017 in co-authorship with DSc, PhD, Eng. Barbara Tchórzewska-Cieślak, prof. RUT and DSc, PhD, Eng. Dorota Papciak, prof. RUT monograph entitled *Estimating the risk of changes in water quality in water supply networks*[58]. Water supplied to customers must be of an adequate quality not only at the moment of entry into the water supply network but also at the point of consumer reception[59]. During transport of water to the recipient often deteriorates its quality caused by the release of the material from which the network is made, the creation and detachment of biofilms, the collection and release of deposited deposits. Irregular changes in the quality of the supplied water can cause physicochemical and microbiological destabilization of the pipeline material and the resulting growths. The safety of CWSS is the ability of the system to perform its

[57] Rak J., Tchórzewska-Cieślak B., Pietrucha-Urbanik K. *Balneotechnique. Qualities of health resorts,* Publishing House of Rzeszow University of Technology, Rzeszow 2010, s. 1-212, ISBN/ISSN: 978-83-7199-618-4.

[58] Tchórzewska-Cieślak B., Papciak D., Pietrucha-Urbanik K.: *Estimating the risk of changes in water quality in water supply networks,* Publishing House of Rzeszow University of Technology, Rzeszow 2017, s. 1-114. ISBN/ISSN: 978-83-7934-207-5.

[59] Regulation of the Minister of Health on the 7th December 2017 *on the quality of water intended for human consumption* (the Official Journal Law item 2294).

functions despite the occurrence of various types of undesirable events [60,61,62,63,64]. In the works entitled *Analysis of chemical stability of tap water in terms of required level of technological safety* and *Analysis of the biological stability of tap water on the basis of risk analysis and parameters limiting the secondary growth of microorganisms in water distribution systems*[65,66] analysis and assessment of the risk of loss of chemical and biological water stability were performed. The effects of loss of stability are increased susceptibility to corrosion and secondary deterioration of organoleptic parameters through secondary water pollution in the network, and thus a threat to consumer health. The analysis was made on the basis of the obtained operational data from the water treatment station. It was assumed that the risk related to failure to meet certain (required) water quality parameters in the water supply network, which may have a negative impact on the physicochemical parameters and bacteriological quality of water reaching the consumer is a measure of the lack of biostability. The risk in this aspect can be defined as the expected value of losses (effects) that may occur as a result of exceeding certain parameters of the quality of tap water. Starting from the definition of the expected value such defined risk is the probability of exceeding the assumed water quality parameters[15,16,17,18,67,68]. The following threshold values for parameters determining the biological stability of water were adopted for risk analysis and assessment[69]: BDOC = 025 gC/m^3, $\Sigma N_{inorganic}$ = 0.2 gN/m^3 and PO_4^{3-} = 0.03 gPO_4^{3-}/m^3.

The following safety levels have been adopted: an acceptable level of safety - SL_T, which corresponds to the parameters defining the area of tolerated risk (r_T), the parameters of the tap water provide the required biological stability in the water supply network. The level of safety

[60] Rak J.: *Risk basis in the functioning of the water supply system*. Publishing House of Rzeszow University of Technology, Rzeszow 2004.

[61] Rak J.: *Reliability of the surface water treatment system. Journal of Scientific Papers of Rzeszow University of Technology*. Civil and Environmental Engineering, 111, Publishing House of Rzeszow University of Technology, Rzeszow 1993.

[62] Rak J.: *Fundamentals of Water Supply System Safety*. Polish Academy of Science, Lublin 2005.

[63] Rak J., Tchórzewska-Cieślak B.: *Methods of Risk Analysis and Assessment in the Water Supply System*. Publishing House of Rzeszow University of Technology, Rzeszow 2005.

[64] Zimoch I.: *Operational Safety of the Water Supply System Under Conditions of Water Quality Variations in the Water-pipe Network*, 2009, Environmental Protection, 31 (3), pp. 51-55.

[65] Pietrucha-Urbanik K., Tchórzewska-Cieślak B., Papciak D., Skrzypczak I. *Analysis of chemical stability of tap water in terms of required level of technological safety*, 2017, Archives of Environmental Protection, 43 (4), pp. 3-12, ISBN/ISSN: 2083-4772.

[66] Papciak D., Tchórzewska-Cieślak B., Pietrucha-Urbanik K., Pietrzyk A. *Analysis of the biological stability of tap water on the basis of risk analysis and parameters limiting the secondary growth of microorganisms in water distribution systems*, 2018, Desalination and Water Treatment, pp. 1-9, ISBN/ISSN: 1944-3994.

[67] Tchórzewska-Cieślak B.: *Methods for analysis and assessment of failure risk of the water distribution subsystem*. Publishing House of Rzeszow University of Technology, Rzeszow 2011.

[68] Tchórzewska-Cieślak B.: *Water supply system reliability management*. Environmental Protection Engineering. 35, 2009, pp. 29-35.

[69] Wolska M.: *Removal of nutrients in the technology of purification of water intended for human consumption*. Publishing House of Wroclaw University of Technology, Wroclaw 2015.

that requires control and reduction - SL_K, corresponds to the level of controlled risk (r_K) and means that water quality parameters indicate the possibility of changes in the chemical stability of water in the water supply network. Unacceptable level of safety - SL_{NA}, determined by unacceptable risk (r_{NA}) means the occurrence of such water quality parameters that cause the lack of biological stability of the water in the water supply network, which in turn may cause its secondary contamination.

The analysis and assessment of the risk of loss of chemical water stability were based on the assumption that secondary contamination of tap water in the distribution system is mainly related to those water properties that determine the precipitation and dissolution of accumulated sediments and directly affect the organoleptic properties of water. It was assumed that the measure of the risk of loss of stability of tap water is the expected value associated with exceeding the water corrosivity indexes, taking into account the tendency to form protective layers and to precipitate and dissolve sediments. For this purpose, the analysis covers Langelier saturation indexes I_L, index of Ryznar I_R and index of Strohecker I_{st}. Operators should participate in the design process of the water distribution system, using appropriate materials to ensure an adequate level of safety from the water source to consumers. It should be noted that it is necessary to adapt the internal material of the water supply network installation to the water parameters. Currently, there is no correlation between the design stage and water parameters. It was stated that in order to protect the water supply infrastructure that belongs to the critical infrastructure, the water supply company should put more emphasis on the distribution of stable water that has no potentially corrosive properties. Some suggestions have been made regarding the protection of the water distribution system and ensuring the safety of the system's operation and the long-term durability of the water pipes.

Another area of research concerned the study of reliability and safety of the functioning of natural gas distribution systems. In the work entitled *Analysis of the gas network failure and failure prediction using the Monte Carlo simulation method*[70] analysis of the failure of gas networks and failure forecasting with the use of simulation methods was performed, which will allow proper classification of subsystem elements for modernization or general overhauls. In the work entitled *Approaches for Safety Analysis of Gas-Pipeline Functionality in Terms of Failure Occurrence: a Case Study*[71] and *Approaches to Methods of Risk Analysis and Assessment Regarding the Gas Supply to a City*[72] a method of forecasting acceptable consequences of failure

[70] Tchórzewska-Cieślak B., Pietrucha-Urbanik K., Urbanik M.: *Analysis of the gas network failure and failure prediction using the Monte Carlo simulation method*, 2016, Eksploatacja i Niezawodnosc - Maintenance and Reliability, Vol. 18, No. 2, pp. 254-259, ISBN/ISSN: 1507-2711.

[71] Tchórzewska-Cieślak B., Pietrucha-Urbanik K., Urbanik M., Rak J.R.: *Approaches for Safety Analysis of Gas-Pipeline Functionality in Terms of Failure Occurrence: A Case Study*, Energies 2018, Vol. 11, No. 1589, ISSN 1996-1073.

[72] Tchórzewska-Cieślak B., Pietrucha-Urbanik K.: Approaches to Methods of Risk Analysis and Assessment Regarding the Gas Supply to a City, Energies 2018, Vol. 11(12), No. 3304, ISSN 1996-1073.

using a homogeneous Markov chain and determination of flow distribution of damage to the gas network using the Poisson distribution were presented

Another area of research was the analysis of the issue of threats related to the functioning of small water supply systems with the background of the assessment of the water consumers safety made on the basis of risk analysis presented in the works entitled *Safety problems of small water supply systems*[73] and *Analysis of the safety of water supply systems in rural areas*[74]. A definition of the measure of the consumers' safety loss of drinking water is proposed as a risk related to the possibility of consumption of poor quality water or its lack. For this purpose, a three-parameter matrix was implemented with the probability parameters of a representative emergency scenario, the effects for water consumers and their protection. Risk management, along with the implementation of protection barriers for small water supply systems against hazards, is the basic condition for the continuity of the system's operation.

In works entitled *Review of methods for identifying threats including the critical infrastructure systems within the Baltic Sea*[75], *Development of cause-effect dependence model of undesirable events using Bayes network*[76] and *Developing procedures for hazard identification*[77] the focus was on the analysis of the functioning of critical infrastructure within the Baltic Sea port. A method of risk analysis using the Bayesian network, which is used in decision-making processes was proposed. A method of cause and effect analysis of undesirable events using the Bayes network using the Java Bayes program was developed. The use of the Bayesian network makes it possible to determine the probability of a peak event and partial events included in the network, which is the basic information for the assessment of system safety. Based on the proposed method, information on the level of risk was obtained (in the adopted five-point scale) will occur with a certain probability. On the basis of the performed analysis, actions were proposed to prevent and limit the emergence of threats and reduce the effects of undesirable events. A procedure for identifying system weaknesses that pose the greatest threat to the security of critical infrastructure has been proposed.

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[75] Tchórzewska-Cieślak B., Pietrucha-Urbanik K., Szpak D.: *Review of methods for identifying threats including the critical infrastructure systems within the Baltic Sea*, 2017, Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars, t.8, z.1, s.139-148, ISBN/ISSN: 2084-5316.

[76] Tchórzewska-Cieślak B., Pietrucha-Urbanik K., Szpak D.: *Development of cause-effect dependence model of undesirable events using Bayes network*, 2017, Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars, t.8, z.1, s.149-156, ISBN/ISSN: 2084-5316.

[77] Tchórzewska-Cieślak B., Pietrucha-Urbanik K., Szpak D.: *Developing procedures for hazard identification*, 2016, Journal Of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars, t.7, z.1, s.209-215, ISBN/ISSN: 2084-5316.

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4. Act dated on the 7th June 2001 *on Collective Water Supply and Sewage* Disposal (the Official Journal Law no. 72, item 747 with subsequent amendments).
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6. SUMMARY OF SCIENTIFIC ACHIEVEMENTS

Before being granted a degree of a PhD I was a co-author of two articles published in journals distinguished in the JCR database, 35 publications in journals scored by the Ministry of Science and Higher Education, 1 publication without a point, 7 chapters in monographs and 4 publications in conference proceedings. The total points according to the Ministry of Science and Higher Education MNiSW for papers in the year of publishing before being granted a degree of a PhD is 253.57 pts.

After being granted a degree of a PhD, my achievements comprise of 62 publications, including 16 articles published in journals distinguished in the JCR database, 38 publications in journals not distinguished in the JCR database but which are in the list of the Ministry of Science and Higher Education, 2 chapters in monographs, 5 publications in conference proceedings. The results of the work were presented on 7 international and 8 national conferences. The total of

IF for articles in the year of publishing is Journal Citation Reports (JCR): 22.713 (IF_{5years} 23.216). Hirsch Index according to Web of Science is 11 (Appendix 7. Analysis of Citations).

The total points according to the Ministry of Science and Higher Education MNiSW for papers in the year of publishing after being granted a degree of a PhD is 482.78 pts.

List of scientific achievements and information on didactic achievements, scientific cooperation and popularization of science is presented in Appendix 3. (List of Published Scientific Papers or Creative Professional Work and Information on Didactic Achievements, Scientific Cooperation and Popularization of Science) and Appendix 6. Analysis of Scientific Achievements.

Katarzyna Pietrucha-Urbanik