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BAYESIAN MODEL OF URBAN WATER SAFETY MANAGEMENT

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ABSTRACT

Water supply system is a critical infrastructure. Main task of urban water system is to provide consumers with drinking water in adequate quantity, at the required quality and pressure corresponding to current standards.

For the purposes of this paper, operational reliability of the water supply system is defined as the ability to supply a constant flow of water for various groups of consumers, with a specific quality and specific pressure, according to consumers demands, in specific operational conditions, at any or at a specific time.

The main aim of this paper is to present a method for risk analysis using Bayesian process. The proposed method made it possible to estimate risk associated with the possibility of partial or total loss of the ability of water supply system operation. The paper proposes to consider two types of risk: the first type, associated with the possibility of interruptions in water supply and the second type, associated with the possibility of tap water contamination.

Keywords: water supply systems, risk analysis, Bayes model

1. Introduction

The Water Supply System (WSS) is a complex technological system, working continuously and requiring a high safety level. The water supply system consists of the subsystems, such as: the Water Intake Subsystem (WISb), the Water Treatment Subsystem (WTSb), the Water Pumping Subsystem (WPSb), the Water Storage Subsystem (WSSb), the Water Distribution Subsystem (WDSb). Reliability of the WSS is the level of the operating of subsystems and objects of this system, resulting in the ability to supply the consumers a required amount of water, with a specific pressure and a specific quality, according to the valid standards and with the acceptable price.

Unreliability of the WSS can be measured by the probability, frequency and duration of the undesirable events. Safety of the WSS means the ability to execute its functions despite of the fact that incidental undesirable events occur.

Urban WSS safety management system is introduced on the level of the local water companies. Risk management is part of a modern and well-developed system of safety management of water supply systems. It is a multi-step procedure aimed at improving the system safety, including quantitative and qualitative aspects of drinking water. This process is based primarily on the risk analysis, risk assessment or risk estimation, making decision on its acceptability, periodic control or reduction (Pietrucha-Urbanik, 2013; Rak and Pietrucha, 2008). Procedures for risk analysis cover the whole activity aiming to identify threats, to estimate risk and its size. Risk identification is based on a selection of representative emergency events that may occur during continuous operation of WSS, including initiating events that could cause the so-called domino effect (Li *et al.,* 2009).

The bayesian networks - BRA (Bayes Risk Analysis) are used in risk analysis due to the ability to model the dependent events. The Bayesian network is upgraded by means of experience and acquired knowledge. The network is modelled by a directed acyclic graph in which vertices represent events and edges represent causal connections between these events. The occurrence of the event X_j (cause) has some impact on the occurrence of the event X_i (effect). If this impact is not "certain" and can only be determined by the probability, then such an arrangement of events and the relation between them can be modelled by a directed graph D (Bernardo and Smith, 1993; Studzinski and Pietrucha-Urbanik, 2012; Tchórzewska-Cieślak, 2007). Each event is represented as a graph vertex. Relations between events are represented by edges. If the occurrence of the event X_j has some impact on the occurrence of the event X_i (X_i depends on X_j), then there is an edge (X_j, X_i) in the graph model, exiting the X_j and entering the X_i (direction is indicated by the arrow). The vertex X_j is called 'parent' of the vertex X_i. The set of all 'parents' of the vertex X is marked as π(X). Most often every event is identified with the corresponding random variable having the same name, on the assumption that all the random variables corresponding to the events are bivalent (1 - an event that occurs, 0 – an event opposed to the event that occurs).The relations between the vertices (events) are expressed by means of the conditional probability. For the vertex X, whose parents are in the set π(X), these relations are represented by the conditional probability tables (CPT). In CPT, for the variable X, all the probabilities P(X|π(X)) (for all the possible combinations of variables from the set π(X)) must be specified. The table for the vertex that does not have parents includes the probabilities that the random variable X will take its particular values.
If the network has n vertices, X_1, ..., X_n, the total probability distribution of all the random variables is shown as the relation (Bishop, 2006):

$$P(X_1, ..., X_n) = \prod_{n=1}^{n} P(X_i | \pi(X_i)) \quad (1)$$

To determine the total probability distribution without using the Bayesian network it is necessary to know all the values of P(X_1, ..., X_n) for all the possible combinations of variables X_1, ..., X_n, which gives 2^n values of the probabilities. Using the Bayesian network it is sufficient to know the conditional probabilities for each vertex.

At the macro scale, safety concerning water supply is defined as a state of water management that allows to cover current and future customers demands for water, in a technically and economically justified way, and by the requirements for the protection of the aquatic environment (Pollard *et al*., 2004; Tchórzewska-Cieślak and Wloch, 2006). The primary and basic subject to which the notion of water safety is concerned is a consumer. The secondary subject is a supplier – a manufacturer of water. In this respect, one can consider the risk of the consumer and the risk of the producer (Pollard *et al.,* 2004; Tchórzewska-Cieślak and Wloch, 2006). The important elements in this regard are also the environmental aspects and the principles of sustainable development in widely understood water management. The definition of water supply safety is the following: "safe operation of water supply systems means ensuring continuity of water supply to the consumer while the following criteria are met: system reliability (for quantity and quality), socially acceptable level of prices per m^3 of delivered water, taking into account the aspects arising from the requirements for public safety, natural aquatic environment protection and the standard of quality of life (Pollard *et al.,* 2004; Rak, 2009; Tchórzewska-Cieślak and Wloch, 2006).

2. Analysis of water consumers risk

Consumer's risk (individual) r_K is the sum of the first kind risk associated with the possibility of interruptions in water supply, and the second kind risk associated with the consumption of poor quality water (Tchorzewska-Cieslak, 2011). Consumer's risk is a function of the following parameters: probability P or frequency f of undesirable events in water distribution subsystem which are directly felt by water consumers, related losses C (e.g. purchase of bottled water, possible medical expenses after consuming unfit for drinking water or immeasurable losses, such as living and economic difficulties and loss of life or health), the degree of vulnerability V to undesirable events (Apostolakis and Kaplan, 1981; Christodoulous *et al.,* 2008; Hastak and Baim, 2001; Pollard *et al*., 2004; Tchorzewska-Cieslak, 2011). Consumer's risk R_C is given by the formula:

$$R_c=R_{CI}+R_{CII} \qquad (2)$$

where:

R_{CI} – the risk of the first type,

R_{CII} – the risk of the second type

For the risk of the first type, associated with quantity of supplied water, and for the risk of the second type, associated with quality of supplied water , the three parametric definition was assumed:

$$R_{CI,II}=P_{iI,II}C_{jI,II}V_{kI,II} \qquad (3)$$

where:

$P_{iI,II}$ - likelihood of event occurrence that may cause the risk of the first type or the risk of the second type,

$C_{jI,II}$ - losses caused by the undesirable event that may cause the risk of the first type or the risk of the second type,

$V_{kI,II}$ - vulnerability associated with the occurrence of the undesirable event that may cause the risk of the first type or the risk of the second type.

3. Risk analysis of water distribution subsystem failure using the bayesian network

The Bayesian network can be used in the decision-making model analysing the risk of failure in urban water system. Risk analysis model for the risk of the first type and the risk of the second type that can be used in making decisions by water supply companies (for the modernization or repairs), was developed. This model was inserted into the calculation program JavaBayes (Tchorzewska-Cieslak, 2011). In Figures 1 and 2 the developed bayesian network influence diagram (BNID), used for failure risk analysis of WDS,are presented.

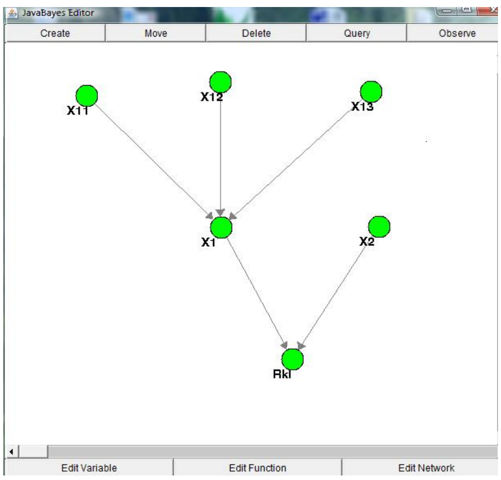

Figure 1. Bayesian network influence diagram, for the risk of the first type (JavaBayes Widow) (Tchorzewska-Cieslak, 2011)

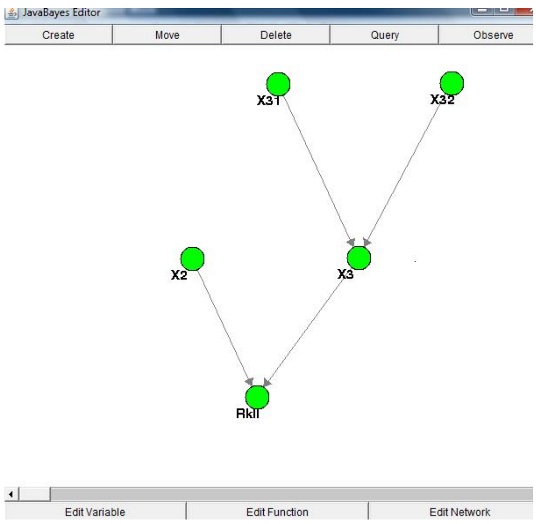

Figure 2. Bayesian network influence diagram for the risk of the second type(JavaBayes Widow) (Tchorzewska-Cieslak, 2011)

Symbols used in Figure 1 and 2 mean:

- $R_{CI,II}$ – consumer's risk (the first or second type) in a five-point scale: $R_{CI,II}=\{r_{C1}, r_{C2}, r_{C3}, r_{C4}, r_{C5}\}$

- negligible risk r_{C1},
- tolerable risk r_{C2},
- controlled risk r_{C3},
- intolerable risk r_{C4},
- unacceptable risk r_{C5}.

• X_1 – interruption in water supply:

- X_{11} – failure of the water supply network,
- X_{12} – lack of water supply from the water treatment plant,
- X_{13} – failure of zone pumping stations.

• X_2 – consumers protection from the existing threat:

- very little – x_{21},
- little – x_{22},
- medium – x_{23},
- large– x_{24},
- very large – x_{25},

• X_3 – water quality parameters specified in the relevant Regulations of the Minister of Health are exceeded:

- X_{31} – physico-chemical parameters are exceeded ,
- X_{32} – microbiological parameters are exceeded.

The following assumptions were made:

- the event in the given node takes exactly one of the possible values,
- 1 means that the event occurs, 0 - that the event does not occur
  For each vertex the CPT should be defined :

For the risk of the first kind (fig. 1):

- $P(R_{CI} | X_1, X_2)$,
- $P(X_1 | X_{11}, X_{12}, X_{13})$,
- $P(X_2)$,
- $P(X_{11})$,
- $P(X_{12})$,
- $P(X_{13})$,

For the risk of the second kind (fig. 2)

- $P(R_{CII} | X_2, X_3)$,
- $P(X_3 | X_{31}, X_{32})$,
- $P(X_{31})$,
- $P(X_{32})$.

Using the formulas (1) the values of probability for each risk category (the first or second kind), i.e. $P(R_{CI,II} = r_{C1}, r_{C2}, r_{C3}, r_{C4}, r_{C5})$, were calculated. An example of reasoning is as follows: the probability that the consumer's risk of the first type is negligible is the sum of the product of the conditional probabilities $P(R_{CI} = R_{CI1} | (X_1 \wedge X_2))$ (the probability that r_{CI} is r_{CI1}, if event X_1 (X_1 = 1,0) and events X_2 (X_2 =

x_{21}, x_{22}, x_{23}, x_{24}, x_{25})) and the probabilities for events X_1 and X_2: $P(X_1) \cdot P(X_2)$. The summation is performed for all the possible values of X_1 and X_2, according to the general formula (Tchorzewska-Cieslak, 2011):

$$P(R_{CI}=r_{C1}, r_{C2}, r_{C3}, r_{C4}, r_{C5},)= \sum_{X=i,j} P(R_{CI}=r_{C1}|X_1=i \wedge X_2=j) \cdot P(X_1=i) \cdot (X_2=j) \quad (4)$$

where:

i – event X_1 occurs or does not occur ; i = 1,0,

j – given value of event X_2; j = x_{21}, x_{22}, x_{23}, x_{24}, x_{25}.

The rest of the values are calculated in the same way. The developed model allows to determine the probability of the particular risk level. The result of modelling are the probability values for each risk level. The risk assessment is based on the interpretation of the result (risk with the highest and the lowest probability of occurrence is given). For example, the result shows that for the first type of risk the highest probability is for a tolerable level and the lowest for the unacceptable level. The developed model enables also determining the partial probabilities for events included in the defined Bayesian network.

4. The application example

The analysed water supply system is located in the south-eastern Poland. The system can be characterized as follows:

- the system is currently used by about 200 thousand residents of the city and nearby towns. The average daily treated water production is about 34 600 m^3/d and it fully meets the customers demand for water.
- surface water from the river is used.
- the water supply system has a total length of about 840 km.
- the main water supply network of the city has a closed system, which is an important feature of the system, if a failure of a given section of the network occurs, location and capacity of the network tanks along with the network system is a vital element for protecting water consumers in case of failure of the water main.
- two teams of water tanks located in the eastern and western part of the city work with the water pipe network. Capacity of network tanks protects about 80% of the supplied area in case of emergency lack of water supply at $0.8Q_{maxd}$,
- monitoring of all water treatment plant facilities operation and two independent technological lines, in conjunction with monitoring of raw and treated water quality parameters, as well as quantitative monitoring carried out in the part of water supply system, allow rapid response to an undesirable event that occurs in the water source.

During the analysis the possibility that the undesirable events will occur was considered (in particular with regard to the possibility of that may cause the risk of the first type or the risk of the second type (2)), such as an accidental pollution of water in the water source, to which the treatment process is not prepared, lack of power supply for water treatment plant, failures of basic components of water treatment station, failure of the main and distribution water pipes causing lack of water supply to the city, global pollution of water in water-pipe network.

The number of failures in the particular kinds of water-pipe network has been analysed, referring to the water-pipe network length. The values of failure rate were calculated according to equation 5.

$$\lambda = \frac{k(t,t+\Delta t)}{L\Delta t} \quad (5)$$

where :

k (t, t+Δt) –a total number of failures in a time interval Δt, in the given kind of network,

l– length of the given kind of network (main, distributive) where failures occurred, in the given time interval [km],

In the analyzed period, the average intensity of failures recorded in the failure dailies by repair teams for water pipes amounted to 278 failures per year, and the corresponding average intensity failure rate was 0.38 tab.1 (Tchorzewska-Cieslak, 2011).

Table 1. Basic statistical characteristics of the failure intensity of water network.

Type of water supply network	Average length of the network L (km)	Average intensity failure [no of failures/a]	λj [no of failures/km·a]			Standard deviation
			λ_{min}	λ_{avg}	λ_{max}	
Mains	49.5	13.1	0.2	0.26	0.36	0.05
Distributional	386.3	156.5	0.24	0.41	0.62	0.14

Table 2. The CPT for r_{CI}

Nr	X_1	X_2					$P(r_{CI} \mid X_1, X_2)$				
		x_{21}	x_{22}	x_{23}	x_{24}	x_{25}	r_{CI1}	r_{CI2}	r_{CI3}	r_{CI4}	r_{CI5}
1	1	1	0	0	0	0	0.05	0.05	0.2	0.3	0.4
2	1	0	1	0	0	0	0.1	0.1	0.3	0.3	0.2
3	1	0	0	1	0	0	0.2	0.2	0.3	0.2	0.1
4	1	0	0	0	1	0	0.3	0.4	0.2	0.1	0
5	1	0	0	0	0	1	0.4	0.3	0.3	0	0
6	0	1	0	0	0	0	0.6	0.4	0	0	0
7	0	0	1	0	0	0	0.65	0.35	0	0	0
8	0	0	0	1	0	0	0.7	0.3	0	0	0
9	0	0	0	0	1	0	0.8	0.2	0	0	0
10	0	0	0	0	0	1	0.9	0.1	0	0	0

Table 3. The CPT for X_1

$P(X_1 \mid X_{11}, X_{12}, X_{13})$	X_{11}	X_{12}	X_{13}
0	0	0	0
0.2	1	0	0
0.05	0	1	0
0.005	0	0	1
0.245	1	1	0
0.1	1	0	1
0.1	0	1	1
0.3	1	1	1

On the basis of the analysis of the operational test of the water supply system and the data obtained from the experts the individual values of probabilities and conditional probabilities of cause and effect for undesirable events for considered water system were determined (Tchorzewska-Cieslak, 2011).

To perform risk analysis in terms of water consumers safety, the developed model using the Bayesian networks was applied. Calculations were performed by means of JavaBayes, using the model for the risk of the first and second kind. For each vertex of the Bayesian network (Figs. 1 and2) the CPT were defined (table 2-8 (Tchorzewska-Cieslak, 2011).

Table 4. The CPT for X_{11}, X_{12}, X_{13}

P(X)	X_{11}	X_{12}	X_{13}
P(X = 1)	0.1	0.3	0.6
P(X = 0)	0.9	0.7	0.4

Table 5. The CPT for X_2

X_2	$P(X_2 = 1)$
x_{21}	0.3
x_{22}	0.5
x_{23}	0.14
x_{24}	0.05
x_{25}	0.01

Table 6. The CPT for r_{CII}

Nr	X_3	X_2					$P(r_{CII} \mid X_2, X_3)$				
		x_{21}	x_{22}	x_{23}	x_{24}	x_{25}	r_{CI1}	r_{CI2}	r_{CI3}	r_{CI4}	r_{CI5}
1	1	1	0	0	0	0	0	0.1	0.2	0.3	0.4
2	1	0	1	0	0	0	0	0.1	0.2	0.4	0.3
3	1	0	0	1	0	0	0.1	0.2	0.3	0.2	0.2
4	1	0	0	0	1	0	0.3	0.3	0.2	0.2	0
5	1	0	0	0	0	1	0.6	0.3	0.1	0	0
6	0	1	0	0	0	0	0.6	0.4	0	0	0
7	0	0	1	0	0	0	0.65	0.35	0	0	0
8	0	0	0	1	0	0	0.7	0.3	0	0	0
9	0	0	0	0	1	0	0.8	0.2	0	0	0
10	0	0	0	0	0	1	0.9	0.1	0	0	0

Table 7. The CPT for X_3

$P(X_3 \mid X_{31}, X_{32})$	X_{31}	X_{32}
0	0	0
0.1	1	0
0.3	0	1
0.6	1	1

Table 8. The CPT for X_{31} i X_{32}

P(X)	X_{31}	X_{32}
P(X = 1)	0.3	0.1
P(X = 0)	0.7	0.9

5. Results

The calculation results are presented in Table 9.

Risk analysis, made with the adopted assumptions, for the analysed water supply system, both in terms of the lack of water supply and the possibility of consuming water with parameters inconsistent with the existing regulation, shows that risk is at the negligible level.

If the calculated values indicate that risk is:

- negligible or tolerable – one can assume that the WSS fulfils its functions in the satisfying way
- controlled – an improvement in the work of some elements or repair of some sections of WSS should be considered
- intolerable or unacceptable –the WSS does not fulfil its functions and should undergo a complete modernization or even redesigning

Table.9. The results of the first kind risk analysis and the second kind risk analysis performed using the Bayesian network

Risk scale	The probability of the particular risk		Risk	
	r_{KI}	r_{KII}	r_{KI}	r_{KII}
negligible	**0,630**	**0,583**	negligible	negligible
tolerable	0,340	0,329		
controlled	0,011	0,022		
intolerable	0,010	0,034		
unacceptable	0,0095	0,0031		

6. Conclusions

The most important in WSS safety operating management is to assess integrated risk and to present this risk in a graphic way in the given territory. Risk estimation is a very useful tool which supports management in crisis.

Analysis of risk connected with the WSS functioning should be the main element of complex WSS risk management. The exploitation of urban WSS should take into account the minimization of water losses, operational and safety reliability. The procedures of the WSS correct designing, construction and operating should be completed with the detailed subsystem failure analyses. A very important role in the procedures of the failure analysis plays the right failure record, as well as opinions and estimations of experts and users.

The Bayesian network shows the cause-effect relation of events. Using the developed method, one obtains information on the level of risk (in the adopted scale) and its probability. In this way, the proposed model can be an important element in the decision making by the subsystem operator. Models can be modified for all the elements of the water supply system. Two models have been developed, for the first kind risk analysis and for the second kind risk analysis. The program also allows determination of the likelihood of the intermediate events included in the Bayesian network. The GIS (geographic information system) program could significantly support the application of the described method in practice

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