CHEMICAL ENGINEERING TRANSACTIONS

VOL. 26, 2012

Guest Editors: Valerio Cozzani, Eddy De Rademaeker

ISBN 978-88-95608-17-4; **ISSN** 1974-9791

A publication of

AIDIC

The Italian Association
of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1226034

Urban Water Safety Management

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Water supply system is a critical infrastructure. For urban water system its main task 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 WSS 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 consumer's demands, in specific operational conditions, at any or at a specific time. The main aim of this paper is to present a method for the risk analysis using Markov process. The proposed method made it possible to estimate the risks 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 contamination of tap water.

1. Introduction

Safety of collective water supply systems (CWSS) has its international legal regulations based on the guidelines of the World Health Organization (WHO) (*Guidelines for Drinking Water Quality*) (WHO, 2005). Failures of CWSS occur in various countries, regardless of the level and sophistication of technology. An example might be a break of water main with a diameter of 1.7 m, in Bethesada, in the suburbs of Washington, in 2008, and a massive failure of water network in May 2010 in Weston (Massachusetts), causing the lack of safe drinking water from municipal water pipe line for about 2 million inhabitants (about 30 cities, including Boston) for a few days. The human factor plays a very important role in the analysis of the causes of failure (Fanelli, 2010). This may relate to errors of the system operators, as well as the intentional or unintentional actions of the third parties (vandalism and even a terrorist attack). The collective water supply system consists of functionally interrelated subsystems, as an integral whole, whose goal is to provide consumers with safe drinking water in a reliable and safe way. In the study it was assumed as a paradigm that the measure of loss of CWSS safety, including quantitative and qualitative aspects of distributed drinking water, is risk understood as a function of the probability or frequency of emergency events, parameters determining the size of the consequences of these events and the degree of vulnerability of water consumers to this type of events. The basic types of emergency events in CWSS include: failures in water pipes and fittings, secondary water pollution in the water supply network, incidental events causing lack of water supply to the distribution subsystem, e.g. contamination of water sources, water treatment facility failures, water contamination in the network tanks, water pumping stations failures. The consequences of the above events can be: lack of water supply to consumers or interruption in water supply, risk for consumers health as a result of bad quality water consumption, financial losses of the waterworks company as a result of the repairs of failures, flushing the network, lack of water sales and the payment of compensation to water consumers, consumers financial losses related, for example, to the need to purchase bottled water, costs of treatment, costs resulting from sanitary and hygienic inconveniences.

Please cite this article as: Tchorzewska-Cieslak B., 2012, Urban water safety mangement, Chemical Engineering Transactions, 26, 201-206 DOI: 10.3303/CET1226034

2. Materials and method

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 contamination of tap water. The following definition of risk was assumed (Kaplan and Garrick, 1981):

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

where:
P – probability of the event which may cause the risk of first or second type
C – value of losses caused by an emergency event,
V – system vulnerability to the occurrence of emergency event.

The following criteria for the assessment of individual risk parameters were proposed:

For the parameter of probability:

- Very low probability - once in 10 y or less often, low probability - once in 5 y, medium probability - once in 2 y, moderate probability - once in 0.5 y, very high probability - once a month and more often.

For the parameter of losses:

- Small losses: drop of daily water production (Q_{dmax}) up to 70% of the nominal water production (Q_n), or interruptions in water supply up to 6 h, isolated consumers complains, local deterioration of water quality, but there is minimal threat to further water quality deterioration,
- Medium losses: $Q_{dmax} \le (50 \div 70)$ % Q_n or interruptions in water supply up to (6÷24> h for individual consumers, drop of water pressure in water-pipe network, financial losses, considerable organoleptic problems,
- Large losses: $Q_{dmax} < 50$ % Q_n or failure in main water-pipe network, interruptions in water supply >24 h for particular housing estates, districts or a whole city, secondary water contamination in water-pipe network.

For the vulnerability parameter:

- Low vulnerability to failure (very high resistance), the network in the closed system, the ability to cut off the damaged section of the network by means of gates, the ability to avoid interruptions in water supply to customers, full monitoring of water-pipe network, covering the entire area of water supply, the possibility to remote control network hydraulic parameters, emergency reserve in network water tanks covering the needs of the city for at least 24 h.
- Medium vulnerability to failure (medium resistance), the network in the mixed system, the ability to cut off the damaged section of the network by means of gates, water mains standard monitoring, measurements of pressure and flow rate, delayed emergency response system, alternative water sources do not cover the needs completely,
- High vulnerability to failure (very low resistance), the network in the open system, lack of water mains monitoring, lack of emergency warning and response system, very limited access to alternative water sources

For CWSS the following operating states were defined (Tchórzewska-Cieślak, 2009a):

- Up state (UPS)-state in which WSS fulfils its functions according to valid legal regulations and consumers expectations for water quantity (the nominal water production capacity $Q_n \ge Q_{dmax}$) and its quality. During system operation some undesirable events can occur, but losses C connected with these events do not influence system ability (they can be omitted), (C=0)
- Partial fault state (PFS)-state which is characterized by short disturbances in the WSS operation, drop of daily water production, ($0.3\ Q_{dmax} \le Q_n < Q_{dmax}$) or breaks in water supply up to 24 h. There are favorable circumstances for the undesirable events escalation. If we assume that the relative value of boundary losses equals one, then $0 < C \le 1$.
- Complete fault state (CFS)–state in which WSS does not fulfil its functions ($Q_n < 0.3\ Q_{dmax}$) or breaks in water supply are longer than 24 hrs for particular housing estates, districts or parts of a city. Consumers are exposed to consume bad quality water. Water quality creates threat to consumers health or lives, $C \ge C_{gr} = 1$.

For the assumed models Markov processes were used in order to determine the particular stationary possibilities of the occurrence of the particular operation states.

- Model A - low vulnerability to failure (good protection).The model takes into account the possibility of removing threat (the so called evaporation) with the intensity of transition μ_1, during operation of the system (as a result of protective barriers activation when threat occurs).The transition of the system to up state always precedes the transitional state PFS with the intensity of transition μ_2.The model assumes that there is a possibility of partial repair of the system (system is conditionally included into operation. A diagram of the model A is shown in Figure 1.

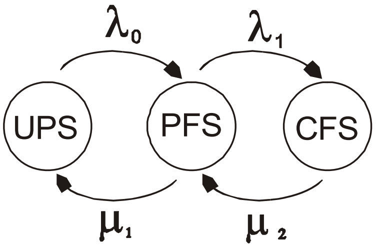

Figure 1. Model A

For the defined model the following assumptions were made (IEC, 2006):

- the occurrence of each state is a random event, transition probabilities corresponding to particular states are: UPS – $P_0(t)$, PFS – $P_1(t)$, CFS – $P_2(t)$, at a given moment system can be only in one of the distinguished states, there is the possibility of states transition, when t = 0 subsystem is in state UPS,

the transition times between particular states have an exponential distribution, parameters of failure rate and repair rate are respectively: λ, μ, a stream of failures is the simplest stream a stationary Poisson stream. The transition matrix is as follows:

$$M(\lambda,\mu)=\begin{bmatrix} -\lambda_0 & \lambda_0 & 0 \\ \mu_1 & -(\lambda_1+\mu_1) & \lambda_1 \\ 0 & \mu_2 & -\mu_2 \end{bmatrix} \tag{2}$$

$$p(0)=\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \tag{3}$$

After solving the system of equations for stationary conditions we obtain the probability of each system state, which can be directly determined by the given values of individual failure rate λ and repair rate μ:

$$P_0=\frac{\mu_1\cdot\mu_2}{\lambda_0\cdot\lambda_1+\mu_2\cdot\mu_1+\mu_2\cdot\lambda_0} \tag{4}$$

$$P_1=\frac{\mu_2\cdot\lambda_0}{\lambda_0\cdot\lambda_1+\mu_2\cdot\mu_1+\mu_2\cdot\lambda_0} \tag{5}$$

$$P_2=\frac{\lambda_0\cdot\lambda_1}{\lambda_0\cdot\lambda_1+\mu_2\cdot\mu_1+\mu_2\cdot\lambda_0} \tag{6}$$

- Model B – medium vulnerability to failure (medium protection). In the proposed model there is the possibility of a direct transition from state UPS to CFS (sudden catastrophic events, e.g. pollution of water intakes connected with serious failures that cannot be reduced by treatment process, water treatment plant is flooded, failure in a strategic pipeline, long-lasting lack of power supply etc), as well as the possibility to evaporate state CFS with the suitable transition intensities λ_2 and μ_2. A diagram of the model is shown in Figure 2.

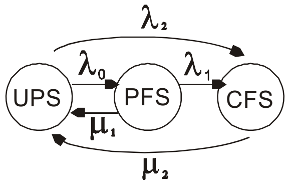

Figure 2: Model B

The transition matrix is as follows:

$$M(\lambda,\mu)=\begin{bmatrix} -(\lambda_0+\lambda_2) & \lambda_0 & \lambda_2 \\ \mu_1 & -(\lambda_1+\mu_1) & \lambda_1 \\ \mu_2 & 0 & -\mu_2 \end{bmatrix} \tag{7}$$

At time t = 0 the system is in UPS (as in model A). After solving the system of equations for stationary conditions we obtain:

$$P_0=\frac{\mu_1\cdot\mu_2+\mu_2\cdot\lambda_1}{\lambda_0\cdot\lambda_1+\lambda_2\cdot\mu_1+\lambda_1\cdot\lambda_2+\mu_2\cdot\mu_1+\mu_2\cdot\lambda_1+\mu_2\cdot\lambda_0} \tag{8}$$

$$P_1=\frac{\mu_2\cdot\lambda_0}{\lambda_0\cdot\lambda_1+\lambda_2\cdot\mu_1+\lambda_1\cdot\lambda_2+\mu_2\cdot\mu_1+\mu_2\cdot\lambda_1+\mu_2\cdot\lambda_0} \tag{9}$$

$$P_2=\frac{\lambda_0\cdot\lambda_1+\lambda_2\cdot\mu_1+\lambda_1\cdot\lambda_2}{\lambda_0\cdot\lambda_1+\lambda_2\cdot\mu_1+\lambda_1\cdot\lambda_2+\mu_2\cdot\mu_1+\mu_2\cdot\lambda_1+\mu_2\cdot\lambda_0} \tag{10}$$

- Model C – high vulnerability to failure (bad protection).This model presents the situation in which during the crisis situation development with time there is no possibility to return from PFS to CFS (domino effect). Only after the occurrence of CFS there is a possibility to remove the threat and to return directly to UPS. A diagram of the model is shown in Figure 3.

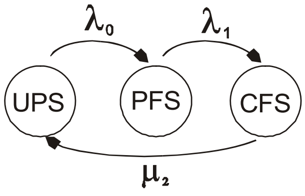

Figure 3: Model C

The transition matrix is as follows:

$$M(\lambda,\mu)=\begin{bmatrix} -\lambda_0 & 0 & \mu_2 \\ \lambda_0 & -\lambda_1 & 0 \\ 0 & \lambda_1 & -\mu_2 \end{bmatrix} \tag{11}$$

At time t = 0 the system is in UPS (as in model A). After solving the system of equations for stationary conditions we obtain:

$$P_0 = \frac{\mu_2 \cdot \lambda_1}{\lambda_0 \cdot \lambda_1 + \lambda_1 \cdot \mu_2 + \mu_2 \cdot \lambda_0} \tag{12}$$

$$P_1 = \frac{\mu_2 \cdot \lambda_0}{\lambda_0 \cdot \lambda_1 + \lambda_1 \cdot \mu_2 + \mu_2 \cdot \lambda_0} \tag{13}$$

$$P_2 = \frac{\mu_0 \cdot \lambda_1}{\lambda_0 \cdot \lambda_1 + \lambda_1 \cdot \mu_2 + \mu_2 \cdot \lambda_0} \tag{14}$$

3. The application example

In order to analyze the risk of losing the ability of CWSS operation in the city of X the Markov processes were used. During the analysis the possibility that the incidental events will occur was considered (in particular with regard to the possibility of total loss of CWSS ability), 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 water pipes causing lack of water supply to the city, global pollution of water in water-pipe network. Based on literature data and operating data the hypothetical values of λ and μ were estimated and then used in the exemplary analysis (Rak, 2009). The system can be characterized as follows: 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. 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 (Tchórzewska-Cieślak, 2009 b). For the assumptions the following formulas to determine the individual values of risk were obtained:

$$r_{PFS} = P_{PFS} \cdot C_{PFS} \tag{15}$$

$$r_{CFS} = P_{CFS} \cdot C_{CFS} \tag{16}$$

where:
r_{PFS} – risk of CWSS PFS partial fault,
r_{CFS} – risk of CWSS CFS fault,
P_{PFS} – probability of CWSS PFS partial fault, P_{CFS} – probability of CWSS CFS fault,
C_{PFS} – possible losses associated with CWSS PFS partial fault, C_{CFS} – possible losses associated with CWSS CFS fault,
The risk in this case takes values from 0 to 1. Based on the experiences described in the publications (Rak, 2009) the criterion values for risk of first and second type were assumed and shown in the three-step scale in Table 1.

Table 1: The criterion values for risk associated with loss of functioning ability for water supply system

Risk level	r_{PFS}	r_{CFS}
tolerable	$\le 10^{-4}$	$\le 10^{-6}$
controlled	$(10^{-4} \div 10^{-2}>$	$(10^{-6} \div 10^{-4}>$
unacceptable	$>10^{-2}$	$>10^{-4}$

For the first type risk analysis, including the risk of lack of water or interruptions in water delivery, the Markov model type A was adopted (Figure 1). The following values of indicators were assumed: $\lambda_0 = 5.5\cdot10^{-4}$ [1/d], $\lambda_1 = 5.5\cdot10^{-5}$ [1/d], $\mu_1 = 3.3\cdot10^{-1}$ [1/d], $\mu_2 = 3.3\cdot10^{-2}$ [1/d], for up state $C_{UPS} = 0$, for partial fault state $C_{PSF} = 2.0\cdot10^{-1}$, for fault state $C_{CFS} = 1,0$.

The results of calculations of individual probabilities and risk r_{PFS}, r_{CFS}:

$P_0 = P_{UPS} = 9.98\cdot10^{-1}$, $P_1 = P_{PFS} = 2.0\cdot10^{-3}$, $P_2 = P_{CFS} = 2.8\cdot10^{-6}$,

and risk value: $r_{PFS} = 4\cdot10^{-4}$ -controlled risk, $r_{CFS} = 3\cdot10^{-4}$ - controlled risk, (according Table 1).

4. Conclusions

With the increasing likelihood of a negative result the level of risk increases. Risk analysis is conducted to determine risk by estimating the probability of the occurrence of undesirable events and their consequences. The value of risk depends on the adopted model, which takes into account level of the subsystem protection against undesirable events. The proposed models take into account different variants of the subsystem protection against incidental events, which enables the use of the proposed method for different specific CWSS. The analysis showed that the risk of CWSS partial fault in the city of X, concerning the lack of water supply to consumers, is at the controlled level and for the complete fault at the tolerated level. This means that the safety of water consumers regarding threat resulting from the occurrence of the incidental events in CWSS in the city is at the required level.

Acknowledgements

Scientific work was financed from the measures of National Center of Research and Development as a development research project No N R14 0006 10: “Development of comprehensive methodology for the assessment of the reliability and safety of water supply to consumers” in the years 2010-2013.

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