Risk assessment methods of a water supply system in terms of reliability and operation cost

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Abstract

Over the past years in Central and Eastern Europe, including Poland, it can be observed that there has been a considerable decrease in water consumption. This leads to high operational costs due to underutilised capacity of existing drinking water treatment plants (DWTP) or distribution systems. Under these conditions providing rational management of DWTP requires technical, economical and reliability analysis. The application of probability and statistical theories together with a decomposition method was the scientific basis of this paper. As a second step, Woodward's LCCA model, together with the Activity Based Costing (ABC) model, were applied.
Keywords: risk, reliability, operation costs, life cycle cost(ing).

1 Introduction

Currently, defining operational reliability of water supply systems is a widely used concept. However, it focuses only on the technical aspects of the system. In this research the authors propose to establish a new concept of "economical reliability", i.e. the system's ability to operate with the lowest possible generated cost. Sand filters are the most common treatment system on DWTP, and the authors have therefore decided to present their new approach on the basis of sand filters.

All calculations were based on actual operational data obtained during the research. This study proposes a practical application of reliability theory.

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2 Material and methods

2.1 Applied formulas and models of reliability

Based on 24 h per day observations conducted from 01.01.2005 to 30.06.2012 every device was characterised in an individual folder. Each folder showed the date of start and end of the operational event, time of renewal, actual repair time, operating time, technical downtime, standby time and a brief description of the event.

Based on a two-parametric method of describing system reliability, and using exploitation data, the following indicators were calculated [1, 2]:

- T_p – average operating time between failures [hr]

$$T_p = \frac{1}{n_p}\left(T - \sum_{i=1}^{n_o} t_{ni}\right) \tag{1}$$

- T_o – average renewal time [hr]

$$T_o = \frac{1}{n_o}\sum_{i=1}^{n_o} t_{ni} \tag{2}$$

- μ – renewal intensity [1/hr]

$$\mu = \frac{1}{T_o} \tag{3}$$

- λ – damage intensity [1/hr]

$$\lambda = \frac{1}{T_p} \tag{4}$$

- f- incidence of damage [1/hr]

$$f = \frac{1}{T_p + T_o} \tag{5}$$

- K – probability of proper operation (dimensionless)

$$K = \frac{T_p}{T_p + T_o} \tag{6}$$

where n_p is the number of segments of working periods in an analysed period, n_o is the number of renewals in an analysed period, t_{ni} is a duration of "*i*" renewal.

2.1.1 Required level of reliability

Based on the research being conducted on Polish water supply systems for over 30 years, required reliability standards were established e.g. value of K indicator depending on the size of the supplied city was calculated by reliability experts [4]. For analysed DWTP, which deliver water to more than 500 000 consumers, the required K indicator equals 0,9827329.

Taking into account that the water production (DWTP) subsystem and the distribution (water pipe network) subsystem are equal in terms of reliability, it was established that the required level of DWTP reliability is:

$$K_{\text{Water Supply System}} = K_{\text{Water Production Subsystem/DWTP}} \cdot K_{\text{Water Distribution Subsystem}} \tag{7}$$

and $$K_{\text{required DWTP}} = \sqrt{0{,}9827329} = 0{,}9913288 \quad (8)$$

Minding, that each step of treatment (i.e. intake, ozone treatment, coagulation, filtration, disinfection) can be considered as a serial subsystems, each of them should be described with K indicator not lower than 0,9982597.

As this research showed pre-ozonation and coagulation subsystems have not experienced significant failures and they have high hydraulic reserve it was assumed that their K indicators are 1,0.

Whereas both DWTP treatment lines are equal (Figure 1), based on analytical equations for homogeneous parallel structure [2], required K indicator of filtration subsystem can be calculated:

$$K_{\text{required for filtration}} = 1 - \sqrt{1 - K_{\text{required for each treatment step}}} \quad (9)$$

$$K_{\text{required for filtration}} = 0{,}9582833$$

2.2 Applied costing methodologies

Risk (reliability) analysis should be regarded as the first step when carrying out an assessment of the operation, followed by a cost analysis.

Based on related literature, it was determined that the most adequate methodology is to apply the concept of Life Cycle Costing (LCC). The aim of LCC analysis is to establish future costs based on an adopted model. Norm PN-EN 60300-3-3 defines LCC as: "total cost incurred during the life cycle of the product." This concept assumes that the life cycle of any object or device can be divided into several phases. Each of them carries some specific cost [5]. For the purpose of this analysis, and based on current literature [6], it was assumed that the object life cycle can be divided into: design, production (construction), usage and disposal.

In each phase the costs are borne by: Company (design, production), User (maintenance and use of the system) and Society (waste disposal, the impact on the health of the population) [6]. The largest part of the cost usually results from the final phases of a product's life, but the design phase gives the greatest opportunity to optimize the total cost of LCC [5].

LCC analysis requires a combination of economic and technical approaches when considering the projected operating/usage time. According to "Guide to cost-benefit analysis of investment projects" by European Commission, a water supply systems' durability is normally 30 years.

For the economic reliability analysis, it was determined that Woodward's LCCA model, together with Activity Based Costing (ABC) by Cooper and Kaplan, are the most relevant.

2.2.1 Model of life cycle analysis (LCCA)

Woodward [8] described that the LCC concept is dependent on: specifying the cost elements of interest, defining the cost structure and cost estimating relationship and establishing the method of LCC formulation.

Furthermore, Kaufman [7] developed the formulation based on an eight-step approach, including:

1. Determine the operating profile (consideration of alternatives);
2. Determine the factors influencing the usage;
3. Define all cost drivers;
4. Identify key cost parameters;
5. Calculate all costs at the current prices;
6. Taking into account the assumed inflation rates;
7. Discounting costs;
8. Sum discounted costs to determine the net present value.

This model is adequate for describing the costs of objects/systems that are in the process of being designed. For systems already in operation it is reasonable to apply the Activity Based Costing model (ABC) [9].

2.2.2 ABC model

This model assigns indirect costs (overhead) and activity costs to the objects, facilities, systems, devices, and uses “cause–effect” relations between factors that generate costs and activities. The ABC concept allows the user to actual allocate the indirect costs, as they are grouped by actions i.e. causes of cost, and requires a detailed study of the structure of incurred costs. The basic classification is defined:

- Direct costs; cost of raw materials, direct wages, wear of equipment used in direct production and technological energy.
- Indirect costs; departmental costs (technical and general), cost of sales, research and development costs and general administrative (overheads) costs.

2.2.3 Cash flows and discounting

Taking into account the relatively long operational life of filters, the economic analysis should include the change of money value over the time. Cash flows occurred at different times should not be directly compared or added together. Rather, all cash flows have to be considered as if at the same point of time. The process by which future cash flows are converted into today’s values is discounting, and the equation below shows the connection between the future and present value of money:

$$PV = \frac{FV}{(1+r)^t} \tag{10}$$

where:

PV – present value e.g. of a cash flow
FV– future value
r – the discount rate
t – the time of the cash flow.

Water supply companies works under specific conditions i.e. they are obligated to provide safe, reliable service with high quality water. From an economic point of view, during the life of the filters, certain cash flows will occur. By cash flows we mean the incoming and outgoing of cash, representing

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the operating activities of an organization [9]. Cost generated during the operation of filters and cash outlays for modernization are considered as cash flows. Filter modernisation will not results in cash income, and for this reason Present Value of Cash Flows (PVCF) is a negative figure and it can be calculated according to equation (4).

$$PVCF = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^n} \tag{11}$$

where:

CF_t – the net cash flow i.e. cash inflow – cash outflow, at time *t*.

For the purposes of this study the minus sign will be omitted.

2.3 Brief description of analysed DWTP

As stated above, the use of sand filters were considered for this demonstration system. However, to fully understand the problem, the background of the DWTP has to be understood.

The filtration system is part of the DWTP which is a one of eleven local water delivery systems and provides water to more than 3 million Silesian citizen. Its design capacity is 500 000 m^3/d; it was built in the 1950s and the present average production is 213 800 m^3/d which equals current water demand. The examined system is one of two parallel filtration subsystems.

The DWTP is provided with the raw water from two independent surface water sources and has two parallel treatment subsystems. First stage treatment is with pre-ozonation chambers; where turbines are provided to ensure contact between the raw water and the ozone. After pre-oxidation, water reaches the distribution chamber. A coagulant (aluminium sulphate) is dosed into the supply pipe serving the Coagulation Building, and the flow is then divided into three separate coagulation lines. Each of the lines has two mixing chambers (labyrinth chambers ensuring turbulent flow), four slow mixing chambers (flocculation) equipped with eight stirrers. The next process is sedimentation, which is carried out in three horizontal sedimentation tanks. The clarified water is then forwarded to a distribution chamber where the flow is divided into two lines, and on to the sand filtration system. The sand filtration system consists of 24 individual filtration chambers. To fulfil the technological requirements each filter is rinsed with process water from a tower tank. After filtration, the treated water flows to the transitional pumping station and via a transitional ozonation system to the active carbon filtration building. The purified water goes directly to the reservoirs, where it is subjected to disinfection with chlorine.

There is a second parallel treatment subsystem based on pre-ozonisation, coagulation in pulsators and sand filtration. The transitional pumping station receives water from both subsystems. The water being fully mixed before being forwarded to carbon filters and then to the reservoirs (Figure 1).

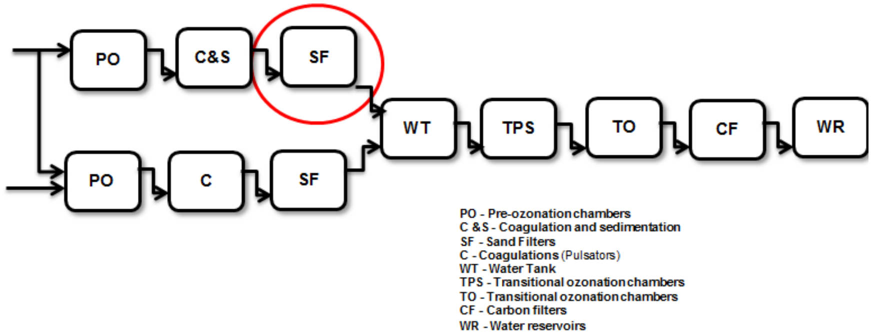

Figure 1: DWTP flow diagram.

3 Results

3.1 Characteristic of sand filtration system

The filtration system consists of 24 identical filter chambers (reinforced concrete) filled with an anthracite bed. The filtration area equals 46 m^2 and the chamber volume is 115 m^3. Each filter bed is provided with 55 cm layer of sand (grain size 0,8-1,4 mm) with a 35-centimeter support layer. The base of the filter chamber is covered by plates with mushroom shape drainage nozzles.

During the research, loss of filter bed material and damage to the drainage plates significantly affected the analysed parameters. As part of the study, due account was taken of the time required for backwash and rearranging the sand beds.

Design filtration velocity equals 6,5 m/h at which the design system efficiency (150,000 m^3/d) is obtained. The current water production reduces this velocity to 1,8–3,0 m/h. The authors were advised that in past years a maximum production of filtration system is 97 700 m^3/d. Taking into account current trend of decreasing water consumption and fact that the probability of a sudden increase is extremely small it was assumed that the maximum required capacity of the filtration system be defined as 97 700 m^3/d rather than the design value. The average productivity of filtration system during the observation period (measured on every 1 hour from 01.01.2005 to 30.06.2012) was 56 304 m^3/d.

Values of the reliability parameters for each filter were determined based on formulas describes in part 2.1 (table 1).

In this study the backwash system was not taken into the analysis as the filter backwash is provided by the tower tank, with the process water being provided by gravity. There are no significant mechanical devices in this system and thus the probability of proper operation (K) equals 1,0.

At the end of the study period there were 24 existing filters of which 18 were in operation, and 6 were out of operation due to drainage plate failure. Filter nos. 4, 6, 7, 18, 20 were damaged from the beginning to the end of the considered period. The drainage plate to filter no. 22 was damaged during the course of the study.

Table 1: Summary of the main reliability parameters of filters.

Filter	λ [1/hr]	T_p [hr]	T_o [hr]	f [1/hr]	K [dimensionless]
No. 1	0,0316081	31,64	0,25	0,0313603	0,9921599
No. 2	0,0316606	31,58	15,25	0,0213536	0,6744530
No. 3	0,0316081	31,64	0,25	0,0313603	0,9921599
No. 4	Filter was damaged during the observation period				
No. 5	0,0316081	31,64	0,25	0,0313603	0,9921599
No. 6	Filter was damaged during the observation period				
No. 7	Filter was damaged during the observation period				
No. 8	0,0316081	31,64	0,25	0,0313603	0,9921599
No. 9	0,0316081	31,64	0,25	0,0313603	0,9921599
No. 10	0,0316081	31,64	0,25	0,0313603	0,9921599
No. 11	**0,0372117**	**26,87**	**9,05**	**0,0278399**	**0,7481501**
No. 12	0,0316081	31,64	0,25	0,0313603	0,9921599
No. 13	0,0316081	31,64	0,25	0,0313603	0,9921599
No. 14	0,0316463	31,6	18,03	0,0201504	0,6367376
No. 15	0,0316081	31,64	0,25	0,0313603	0,9921599
No. 16	0,0316081	31,64	0,25	0,0313603	0,9921599
No. 17	0,0316350	31,61	18,32	0,0200285	0,6331126
No. 18	Filter was damaged during the observation period				
No. 19	0,0316081	31,64	0,25	0,0313603	0,9921599
No. 20	Filter was damaged during the observation period				
No. 21	0,0316081	31,64	0,25	0,0313603	0,9921599
No. 22	0,0316212	31,62	9,75	0,0241713	0,7644022
No. 23	0,0316081	31,64	0,25	0,0313603	0,9921599
No. 24	0,0316081	31,64	0,25	0,0313603	0,9921599

3.2 Reliability and risk analysis

Average measured DWTP production is 56 304 m^3/d and the average estimated filtration velocity equals 2,83 m/h (18 filters in operation). Taking into consideration average production and an optimal filtration velocity (6,5 m/h) it was established that 8 filters is the minimum number of filters that must be in operation at any one time. Having regard, that every 32 hours one filter has to be backwashed, the minimum number of required operational filters is therefore 9.

As a part of the assessment, the maximum DWTP production was analysed. It was calculated that to obtain 97 700 m^3/d, 14 filters must operate with max, design filtration velocity (6,5 m/h). Considering the backwash regime, the minimum required number of operational filters equals 15.

For both cases (required operational 9 and 15 filters) the filtration velocity over each process phase was inspected, and found to be as follows (table 2).

Simulation of different operational conditions were carried out, and the results are shown in tables 3 and 4.

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Table 2: Filtration velocity in each process phase.

No. of maintained filters	Filtration velocity during normal system operation [m/h]	Filtration velocity during backwashing of one filter [m/h]
9	5,7	6,4
15	5,9	6,3

Table 3: Summary of reliability parameters for “9 of n” structure.

Filters' system structure	λ [1/hr]	T_p [hr]	T_o [hr]	f [1/hr]	K [dimensionless]
9 of 18	1,94E-10	5,16E+09	4,02E-02	1,94E-10	1,0000000
9 of 19	3,73E-12	2,68E+11	3,47E-02	3,73E-12	1,0000000
9 of 20	6,60E-14	1,51E+13	3,05E-02	6,60E-14	1,0000000
9 of 21	1,09E-15	9,18E+14	2,72E-02	1,09E-15	1,0000000
9 of 22	1,69E-17	5,90E+16	2,45E-02	1,69E-17	1,0000000
9 of 23	2,51E-19	3,99E+18	2,24E-02	2,51E-19	1,0000000
9 of 24	3,56E-21	2,81E+20	2,05E-02	3,56E-21	1,0000000

Table 4: Summary of reliability parameters for “15 of n” structure.

Filters' system structure	λ [1/hr]	T_p [hr]	T_o [hr]	f [1/hr]	K [dimensionless]
15 of 18	**7,58E-02**	**1,32E+01**	**0,30**	**7,41E-02**	**0,9777574**
15 of 19	1,18E-02	8,50E+01	0,16	1,17E-02	0,9981600
15 of 20	9,94E-04	1,01E+03	0,10	9,94E-04	0,9998999
15 of 21	5,63E-05	1,78E+04	0,07	5,63E-05	0,9999959
15 of 22	2,42E-06	4,12E+05	0,06	2,42E-06	0,9999999
15 of 23	8,54E-08	1,17E+07	0,05	8,54E-08	1,0000000
15 of 24	2,58E-09	3,88E+08	0,04	2,58E-09	1,0000000

3.3 Cost analysis

3.3.1 Costs and cash outlays related to LCC of new filter

In order to provide full LCC assessment the authors have carried out a costs investigation, and the following costs have been determined:

- **Design phase**

This phase included costs related to the provision of executive design, all necessary expertise surveys, land surveys together with obtaining all required permits.

In this phase, risk assessment should be provided to determine the optimal number of filters necessary to ensure the safety of the water supply.

- **Production (construction) phase**

The costs of this phase [10] consist of:

1. Direct costs associated with the purchase and installation of materials and equipment
2. The value of construction and assembly works
3. The value of installed machinery and equipment
4. The value of direct used materials, direct labor costs
5. Fees and charges related to required permits
6. The costs of preparing the construction site
7. Wage of designer and inspectors' supervision
8. Cost of tests and technological commissioning
9. Costs of building insurances.

- **Usage phase**

In the life cycle of the sand filter the backwash time plays the major role. In the analyzed case the backwash time equals 0,25 h, and in accordance with the ABC concept costs are being generated during this 0.25 h period.

1. Rising regime results in following costs:
   - wages of employees directly involved in this process
   - consumed energy supplies pump unit (pump provides purified water to the tower tank)
   - cost of used backwash water
2. The cost of possible repairs can be illustrated by an average renewal time $T_{o.}$ For this study the highest T_o was taken into account. However, during data analysis it was noted that on average once every 10 years, a filter must be renovated, i.e. the anthracite bed must be replaced. This operation requires the emptying of the filter chamber, removal of the filter bed, disposal of sand and provision of new filter bed material.

For this research, it was assumed that the sand filter has an operational life of 30 years.

- **Disposal**

The cost of this phase is mainly the cost of dismantling works and associated disposal. As the filter chambers are reinforced concrete structures, the authors assumed that the structure will be not demolished. Profit from the sale of dismantled scrap metal in this case is negligible.

3.3.2 Costs related to LCC of already operating filter

Basing on the values described above, the LCC of an already operating filter is a sum of costs of the usage and disposal phases.

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Table 5: Costs and cash outlays in each filter's life phase.

Phase of filter's life cycle	Value (pln)
Design	300 000
Production	1 277 000
Usage	2 769 946,46
Disposal	19 898,46

3.4 Indicator of operational readiness

The currently available literature, does not define the concept, or index, joining both reliability and cost factors. The authors of this study propose to introduce indicator of operational readiness (R_i), describing the probability of economic readiness for different (i)operational states.

For the considered filtration system the following indicator was established:

1. First operational state – the most likely production, i.e. 56 304 m^3/d the **economical operational readiness rate (R_e)** was determined:

$$R_e = \frac{K_o \cdot CF_o}{K_n \cdot CF_w} \tag{12}$$

where:

K_o – probability of proper operation of structure "x of y" where "x" is the number of filters necessary for average water production rate and "y" is the number of filters able to operate (here 9 of 18).

CF_o – total cash flow related to the number of filters able to operate (here: 18 filters minding usage and disposal phases).

K_n – probability of proper operation of structure "x of y" where "x" is the number of filters necessary for average water production rate and "y" is the number of all existing filters (here 9 of 24).

CF_w – total cash flow which will occur when whole filtration system will be fully operational (i.e. sum of 18 filters' usage and disposal costs plus cost of 6 filters' design, production, usage and disposal costs).

The equation can be also written as:

$$R_e = \frac{K_{9of18} \cdot CF_{18}}{K_{9of24} \cdot CF_{24}} \tag{13}$$

2. Second operational state – maximum production (97700 m^3/d) it was established (table 4) that structure 15 of 18 is described with the lowest K index higher than required ($K_{\text{required of filtration}} = 0{,}9582833$). Using equation (2) the **target operational readiness rate (R_t)** can be calculated:

$$R_t = \frac{K_s \cdot CF_s}{K_m \cdot CF_w} \tag{14}$$

where:

K_s – probability of proper operation of the structure which is described with the lowest K index but higher than required (here: 15 of 18)

CF_s – total cash flow related to the structure which is described with the lowest K index but higher than required (here: 18)

K_m – probability of proper operation of the structure "x of y" where "x" is the number of filters necessary for max water production rate and "y" is a number of all existing filters (here 15 of 24)

The equation can be also written as:

$$R_t = \frac{K_{15of18} \cdot CF_{18}}{K_{15of24} \cdot CF_{24}} \tag{15}$$

3. Third operational state includes both most likely and maximum water production. Basing on the assumptions above the **critical operational readiness rate (R_c)** can be determined as:

$$R_c = \frac{K_o \cdot CF_o}{K_n \cdot CF_w} \tag{16}$$

Considering the symbols above:

$$R_c = \frac{K_{9z18} \cdot C_{18}}{K_{15z24} \cdot C_{24}} \tag{17}$$

Table 6: Values of operational readiness rate (R).

Operational readiness rate	Value
R_e	0,6571361
R_t	0,6425197
R_c	0,6571361

4 Discussion of the results

1. In this study for the first time a new approach to reliability and costing aspects of DWTP operation was presented. The authors of this paper proposed to implement a new index – operational readiness rate (Ri) for defining different (i) operational states.
2. In analysing the results of this study it can be seen that even for maximum water production 18 filters provides a safe service i.e. K index is higher than required (0,958283257). What is more, when considering the Life Cycle Costs and operational readiness rate, the economic rate is higher than the target rate, which allows one to assume

that operating a structure of 18 filters is sufficient in both economic and reliability terms.

3. Looking for a scientific solution for the DWTP Operators' current problems has led to the development of reliability and economic theories which, when supported by advanced computer software, can be put into practice.

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