Environment Protection Engineering

Vol. 36 2010 No. 4

IZABELA ZIMOCH*, EWA ŁOBOS**

APPLICATION OF THE THEIL STATISTICS TO THE CALIBRATION OF A DYNAMIC WATER SUPPLY MODEL

This paper presents the procedures of the construction and calibration of hydraulic water supply system (WSS) models. In the research, the WSS in Cracow was used. The hydraulic model was built using the EPANET 2 computer program. For the evaluation of compatibility between operating parameters (pressure) obtained by simulation and real pressures in selected nodes (which form two time series) the Theil inconsistency statistics were applied. The method is not a very time consuming and allows us to find nodes at which the difference between the two time series is caused by a systematic error.

1. INTRODUCTION

Water supply system (WSS) is an integral object consisting of many technical elements which realize strictly defined exploitation processes such as water intake, its treatment and distribution. The current regulations of rational management of WSS states that its work is determined not only by changeable quality and quantity parameters of water intake or variable water demand. The principle of consumer acceptance of the conditions and reliability of water supply should be also taken into consideration. The above mentioned regulations affect the economic sphere of water company activity.

Both reliable and economic aspects of exploitation conditions are constantly assessed by consumers and water producers. This is the reason why the rules of exploitation management have to be continuously improved, i.e. their technical, economical and reliable operating aspects [1], [2]. Three parts of WSS management, i.e. highly effective treatment technologies, numerous water-pipe network modernizations, which improve the technical and sanitary conditions, and the optimization of hydraulic exploitation parameters of distribution subsystem ensure high quality of water delivery

* Institute of Water and Sewage Engineering, Silesian University of Technology, Konarskiego 18, 44-100 Gliwice, Poland, tel. (032) 237 28 84, 237 27 27, mobile: 606 62 41 96. E-mail: Izabela.Zimoch@polsl.pl

** Institute of Mathematics, Silesian University of Technology, 44-100 Gliwice, Kaszubska 23, Poland. E-mail: Ewa.Lobos@polsl.pl

for consumers [3]–[6]. Although these improvements minimize the operational risk of contemporary water companies, they simultaneously generate unavoidable costs which influence the price of water. Of course, the increase of water price is limited by consumer acceptance. Therefore water companies face a problem of the necessity to limit costs and maintain exploitation efficiency [7]–[10].

Nowadays, there is a wide choice of professional computer programs which help in modern management of those technical systems. They are applied to: numerical modelling of water supply process, the monitoring of quality and quantity parameters in water treatment technological systems as well as water-pipe systems for GIS (Geographical Information System) formation, etc. They are also useful in the global assessment of water system operation and determination of their critical points in the water production and distribution subsystems, they are a part of the technological process and an engineering solution. Numerous dynamic mathematical models of WSS are used in different simulations of random events. On the basis of computer simulation results one chooses the activity which minimizes the effects of critical operation events and minimizes the risk of water companies activity and increases consumer safety. The above mentioned management instruments give measurable effects such as the efficient use of the existing infrastructure of water supply system, they also generate huge savings in exploitation processes.

The practical application of mathematical models requires a prior calibration process. Usually the calibration process is very difficult to carry out. Another difficulty is the evaluation of the compatibility of time series obtained in simulation and the real values of the examined parameters. A tool which is very useful and convenient in such a situation are the Theil inconsistency statistics.

2. THE THEIL INCONSISTENCY STATISTICS

The Theil inconsistency statistics are used, among other things, in system dynamics to evaluate the goodness-of-fit of simulating models to real data [11]. Suppose that two time series X_t and Y_t, $t = 1, 2, ..., n$ (where n is the number of observations), are considered. Let X_t be a series of observed data and Y_t – series of corresponding simulated data (forecast). The main idea of the Theil statistics relies on the decomposition of mean square error $\sigma^2 = \frac{1}{n}\sum_{t=1}^{n}(X_t - Y_t)^2$ into three parts:

$$\sigma^2 = (\overline{X} - \overline{Y})^2 + (S_X - S_Y)^2 + 2(1-r)S_X S_Y, \qquad (1)$$

where:

$\overline{X}$, $\overline{Y}$ are sample means of series X_t and Y_t, respectively,

S_X, S_Y are sample standard deviations of X_t and Y_t,

r is the sample correlation coefficient between the observed and simulated data.

The Theil statistics are defined as:

$$U^M = \frac{(\overline{X} - \overline{Y})^2}{\sigma^2} \text{ (the bias proportion),} \tag{2}$$

$$U^S = \frac{(S_X - S_Y)^2}{\sigma^2} \text{ (the variance proportion),} \tag{3}$$

$$U^C = \frac{2(1-r)S_X S_Y}{\sigma^2} \text{ (the covariance proportion).} \tag{4}$$

Of course, $U^M + U^S + U^C = 1$. Note that U^M gives information how far the mean of forecast is from the mean of actual series, U^S states how far the variation of forecast is from the considered series X_t, and U^C measures the remaining unsystematic forecasting error.

There are three acceptable situations which indicate unsystematic (random) error of the simulating model:

(i) U^C is close to 1 and both U^M and U^S are close to 0;

(ii) U^S is close to 1, both U^M and U^C are close to 0, and additionally $Y_t = k = \text{const}$, $X_t = k + \varepsilon_t$, where $\frac{1}{n}\sum_{t=1}^{n} \varepsilon_t = 0$;

(iii) $U^M = 0, U^S = \alpha, U^C = 1 - \alpha$.

Other variants of the values of the triple (U^M, U^S, U^C) show that the simulating model has a systematic error.

3. WATER SUPPLY SYSTEM OF CRACOW

The current water supply system of Cracow was built for 100 years. This long construction process encompassed building water treatment plants, their modernization and water-pipe network development resulting from building new housing on the outskirts of the city. The system consists of two complex subsystems: water production subsystem (WPS) and water distribution subsystem (WDS). In the water production subsystem, there are water supply arrangements (WSA), which consist of separated treatment lines fed by surface water sources from the Rudawa, Dłubna, Sanka rivers, the Dobczyce reservoir and underground water from intake in Mistrzejowice.

The technological parameters of the above arrangements are presented in table 1. The present rate of production yield of the WSA is the reason why the Cracow WSS is considered to be a redundancy system. Now the system uses only 46% of its maximal water production efficiency [12].

Table 1

Parameters of water supply arrangements [12]

Water supply arrangement (WSA)	Supply source	Mean production (m^3 per day)	Max production (m^3 per day)	Water production efficiency (%)	Technological system of treatment
Raba WSA	Dobczyce reservoir	77 768	207 000	38	Primary ozonization, coagulation, fast filtration, chlorine disinfection
Bielany WSA	Sanka river	13 476	21 000	64	Slow filtration, chlorine disinfection
Rudawa WSA	Rudawa river	29 441	55 200	53	Coagulation, filtration, active carbon sorption, ClO_2 disinfection
Dłubnia WSA	Dłubnia river	22 433	32 200	70	Coagulation, periodically fine active carbon sorption, fast filtration, ClO_2 disinfection
Mistrzejowice WSA	Underground water	5 141	6 000	87	Preventive sodium hypochlorite disinfection
	Total	**148259**	**321400**		

The water distribution subsystem has delivered water to Cracow inhabitants since 1901. Nowadays the subsystem consists of complex water-pipe network with many pure water tanks. Cracow is divided into separate water-pipe zones which are fed from independent sources. The localization and engineering solutions of the supply systems with water treatment plants ensure reliable operation of WPS in the city (in normal conditions of exploitation).

Table 2

The material structure of the Krakow water-pipe network [13]

Material	The length of network pipes (km)			
	Transit and main pipes	Distributing pipes	Waterworks terminals	Total length
Grey cast iron	103.5	333.4	43.8	480.7
Steel	138.8	199.3	262.8	600.9
AC	–	65.3	–	65.3
PCV	14	407.0	4.4	425.4
PE	9.6	126.1	161.9	297.6
Total	265.9	1131.1	472.9	1869.9

The city supply zoning results from the configuration of the Cracow area. It determines the position and the range of separate zones. There exist thirteen different pressure zones that incorporate areas from 225 m to 366 m elevation above sea level. The reliability of water delivery to the inhabitants of high zones is ensured by hydrophones and intermediate pumping stations. At present the total length of the network in the area serviced by the City of Cracow Water and Sewage Utility Company (MPWiK SA Kraków) is about 1900 km. Over half of the network is built of steel and grey cast iron (table 2) [13].

The current large water distribution system of Cracow consists of transit network pipes diameter ∅1400, its total length is 18 km. The main network of the system is made of pipes from ∅1200 to ∅350 in diameter and its total length is 247.9 km. The greatest part of the system (with regard to the length) is made of distributing pipes from ∅280 to ∅80 in diameter, its total length is 1131.1 km. The last linear element of the discussed subsystem are service pipes, it is a system of 472.9 km of pipes from ∅100 to ∅25 in diameter. Because the water-pipe network has been exploited for over 100 years it is characterized by essential age diversity. There still are some city pipelines from the first decades of the distribution system operating period.

The efficiency of distribution subsystem functionality depends also on the exploitation of the network equalizing and storage tanks. Now in Cracow there are eleven tank complexes in operation with the total capacity of 276,200 m^3. They are mainly storage terrain tanks with single- or multi-chamber system of reinforced concrete construction. Particular attention should be paid to the greatest tank complex Siercza storing 158,500 m^3 of water from the Raba supply arrangement, which is almost a daily requirement in the city. So much treated water stored (about 163% of Q_{av}) in the city increases the reliability of the Cracow waterworks and decreases the water company risk of not fulfilling its primary function – supplying water to consumers [13], [14].

4. THE DYNAMIC HYDRAULIC MODEL OF CRACOW WSS

The mathematical modelling of water-pipe network hydraulic operation is a difficult and complicated problem. Its solution requires interdisciplinary attitude to diverse exploitation factors. Professional scientific literature [8], [11], [15]–[23] gives examples of computer software use in forecasting models of hydraulic parameters of WDS operation. Popular software, applied by engineers and researchers to simulations of various technical issues, includes programs such as EPANET, PICCOLO, Mike Net, ISYDYW. They allow us to compute water flow and pressure in the pipe if the initial conditions of system exploitation are defined.

The most popular simulation program is EPANET which was developed by Rossman's team at U.S. Environmental Protection Angency [24]. The results of EPANET simulations are credible if the assumptions are made:

– the modelled flow in pipes is the pressure flow,
– water compressibility and pipe elasticity are not considered in the modelled system.

Mathematical hydraulic model of the Cracow WSS was developed using EPANET 2 computer program. Among the parameters of hydraulic simulations using EPANET 2 there are the pressure in the junctions of the model and the flows. These parameters allow us to describe the hydraulic model of a water-pipe network as the function of a two-model category: junctions and links of the model. The model of the system junctions is based on the principle of conservation of mass (principle of the flow continuity) and the model of pipe connections is based on a principle of conservation of energy. The above mentioned principles allow us to balance water flow in a distribution system. The balance of energy by Bernoulli's formula (1) is the primary rule of mathematical simulation of the first group of hydraulic model equations of a water-pipe network [8], [14]–[17]:

$$\frac{p_1}{\gamma_w} + z_1 + \frac{v_1^2}{2g} = \frac{p_2}{\gamma_w} + z_2 + \frac{v_2^2}{2g} + \sum h\,, \tag{5}$$

where:

p_1, p_2 – pressures at nodes 1 and 2 (N/m^2),
γ_w – specific gravity of water (N/m^3),
z_1, z_2 – geometrical heads of nodes 1 and 2 (m),
v_1, v_2 – mean velocities at nodes 1 and 2 (m/s),
g – gravitational acceleration (m/s^2),
Σh – sum of head losses (m).

The second group of hydraulic model equations of water distribution system (6) are mass balance formulas at the nodes of network [8], [14]–[17]:

$$\forall n \in N: \quad \sum_{\substack{l \in L_{n+} \\ l \neq l_{d_n}}} Q_l(t) - \sum_{\substack{l \in L_{n-} \\ l \neq l_{p_n}}} Q_l(t) = Q_{l_{p_n}}(t) - Q_{l_{d_n}}(t)\,, \tag{6}$$

where:

n – node of the model,
N – the whole number of model nodes,
l – model link,
L – the whole number of model links,
+/– – input and output indexes,
t – simulation time (s),
$Q_{l_{p_n}}$ – water demand in node (m^3/s),
$Q_{l_{d_n}}$ – water delivered to node (m^3/s),
$Q_l(t)$ – intensity of water inflow and outflow from link l (m^3/s).

The Cracow WSS simulation model of EPANET takes into account all water intakes of the system: WSA Raba, WSA Dłubnia, WSA Rudawa, WSA Bielany and WSA Mistrzejowice. The nodes of the model were unambiguously defined by defining their space coordinates x, y and z, the volume of daily water demand and the demand category (figure 1a). In the process of schematizing the topography of the water pipeline network, all main and distribution pipelines and network terminals of diameter above 100 mm were taken into consideration (figure 1b). The complete identification of the links of the model was achieved by defining their diameter, length, start and end nodes, material of the link pipe, its age and the roughness factor. The process of hydraulic ageing of steel and grey cast iron pipes during their exploitation is described (based on applied research provided in 2005 and research methodology introduced by Professor Zbigniew Siwoń [25]) by mathematical dependencies between conventional equivalent interior surface roughness of pipes k_{to} and the pipe age (table 3).

a) Daily demands at nodes b) Diameter structure of links

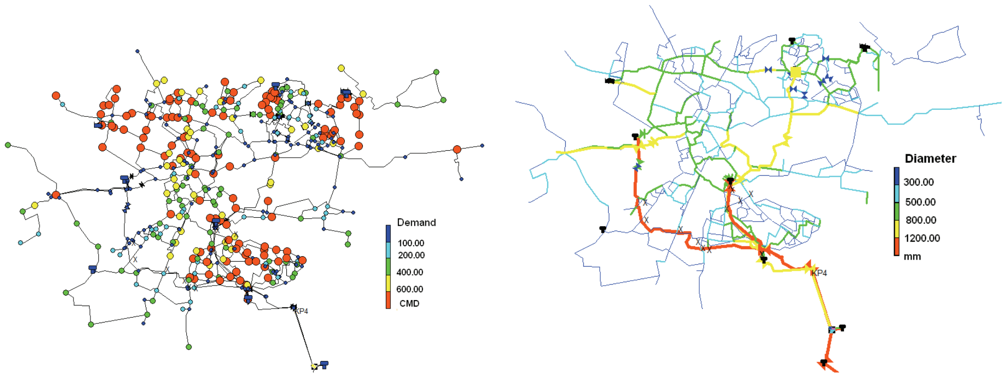

Fig. 1. Selected elements of the hydraulic model of Cracow WSS

Table 3

Conventional equivalent interior surface roughness of pipes k_{t0}
for selected zones of Cracow WDS

Water pipe network	Formula for k_{t0}	Characteristics of research zones	
		Pipe diameter (mm)	Pipe age (years)
Distributing pipes	$k_{t0} = 0.3 + 0.340 \cdot t$	100 ÷ 150	20 ÷ 64
Main pipes	$k_{t0} = 0.3 + 0.228 \cdot t$	200 ÷ 500	13 ÷ 108
Transit pipes	$k_{t0} = 0.3 + 0.197 \cdot t$	600 ÷ 800	10 ÷ 83

In the spatial structure of the hydraulic model of Cracow, the central pumping station Nastawnia Piaski Wielkie was taken into consideration. Other elements of the model are seven water tanks (Kościuszko, Kosocice, Krzemionki, Krzesławice Dolne and Górne, Siercza, Gorzków) with the total storage capacity of 90% of the water in the system. The mathematical model of the Cracow WSS contains patterns of hourly water demand variety which are based on real operation parameters of the system from the exploitation period between 2004–2006. The above model of the Cracow WSS is composed of 493 nodes, 657 links, 5 supply sources, 7 pumps and 24 valves (figure 1), [13], [14].

The above mathematical model of the Cracow WSS was developed during the research conducted as part of project PB No. 5T07E 44 25 and next it was subjected to calibration at 26 selected test nodes [14]. The diverse water production (table 4) forced the calibration of the hydraulic model for different exploitation conditions: average, minimal, and maximal quantities of water production per day.

Table 4

Operating parameters of the Cracow WSS

WSA	Unit	Exploitation conditions – daily water production		
		Average	Minimal	Maximal
		1–7.07.2007	04.07.2007	02.07.2007
System	m^3/d	150 644	138 600	155 388
	%	100.0	100	100
Raba WSA	m^3/d	79 469	70 318	83331
	%	52.8	50.8	53.6
Bielany WSA	m^3/d	12 726	12 725	12 712
	%	8.4	9.2	8.2
Dłubnia WSA	m^3/d	26 351	25 805	26 421
	%	17.5	18.6	17.0
Rudawa WSA	m^3/d	27 325	24 976	28 126
	%	18.1	18.0	18.1
Mistrzejowice WSA	m^3/d	4773	4 776	4 798
	%	3.2	3.4	3.1

The water production reserve of WSS Cracow and large quantity of water stored in tanks enable the optimization of system operation with respect to exploitation costs. There is a weekly recurrent cycle of work in the system, therefore the period of seven days was accepted for the calibration of the hydraulic parameters (flow and pressure) of the model. In the calibration process, 168 measurements of flow and pressure were collected at each test node. Next, these observed values (that form time series of variety per hour) were compared with the corresponding time series built of values from simulations. For the evaluation of goodness-of-fit the Theil statistics U^M, U^S, U^C were applied. The statistics allowed us to determine the value of hydraulic model error resulting from the comparison of the observed time series with its forecast. The obtained inconsistencies between the simulated and real hydraulic parameters follow from the weakness of model or from the randomness of variables.

The calibration process was carried out twice: the first stage in 2006 (February, April, June, July, August, October, December), the second one from April to July

2007. The final results of the Theil statistics obtained for pressures at the considered nodes are presented in table 5. In most cases, the values of statistic U^C are close to 1 whereas the statistics of U^M and U^S are both close to 0 (which was described as acceptable situation (i) in part 2 of the paper). The evaluation results of the model calibration indicate only unsystematic error, which is acceptable in the simulation of dynamic models. At points P9 for minimal and maximal exploitation conditions and at P10 for all exploitation conditions, the situation similar to situation (ii) is observed. At these points the simulated time series is constant because in the real WSS there are pumps which operate at constant rate of delivery. Hence the model is well calibrated – the values of the Theil statistics indicate the existence of random (i.e. unsystematic) error.

Table 5

The Theil inconsistency statistics for the Cracow WSS model

Measuring node	Average capacity of WSS			Minimal capacity of WSS			Maximal capacity of WSS		
	U^M	U^S	U^C	U^M	U^S	U^C	U^M	U^S	U^C
P1	0.059382	0.161366	0.779231	0.153937	0173530	0.672534	0.185309	0.077210	0.737481
P2	0.000160	0.287478	0.787478	0.029044	0.269050	0.701906	0.019521	0.191778	0.788701
P3	0.005294	0.160734	0.833972	0.090114	0.388804	0.521082	0.120833	0.309180	0.569987
P4	0.003385	0.075640	0.920975	0.265783	0.002783	0.731435	0.202850	0.001219	0.795931
P5	0.003350	0.063988	0.932662	0.122158	0.004235	0.873606	0.261307	0.002626	0.736067
P6	0.071262	0.003360	0.925378	0.130330	0.012718	0.856952	0.068129	0.010583	0.921288
P7	0.000148	0.198261	0.801591	0.004041	0.054756	0.941203	0.007009	0.345222	0.647769
P8	0.001300	0.139133	0.859566	0.001445	0.000962	0.997593	0.011508	0.208894	0.779598
P9	0.005327	0.041191	0.953483	0.184916	0,815084	0	0.025586	0.974414	0
P10	0.100396	0.899604	0	0.185943	0.814057	0	0.013706	0.986294	0
P11	0.003211	0.184324	0.812465	0.141245	0.180714	0.678041	0.009695	0.143255	0.847050
P12	0.219214	0.018382	0.762404	0.185572	0.123891	0.690537	0.230303	0.028142	0.741556
P13	0.020744	0.025949	0.953307	0.006898	0.079465	0,913637	0.004852	0.248591	0.746557
P14	0.015343	0.269948	0.714709	0.300972	0.120335	0.578694	0.065252	0.329118	0.605630
P15	0.069286	0.170320	0.760394	0.033012	0.135453	0.831535	0.216158	0.033063	0.750778
P16	0.346177	0.036935	0.616888	0.116471	0.300488	0.583041	0.255813	0.005902	0.738284
P17	0.199552	0.105837	0.694611	0.274469	0.200136	0.525395	0.168170	0.000215	0.831615
P18	0.002541	0.003225	0.994235	0.036291	0.011334	0.952375	0.045939	0.034887	0.919174
P19	0.068791	0.346609	0.584599	0.011535	0.337415	0.661050	0.051897	0.350630	0.597473
P20	0.026812	0.304989	0.668199	0.000006	0.146799	0.853195	0.019938	0.068907	0.911155
P21	0.011330	0.296565	0.692104	0.001443	0.339982	0.658575	0.344222	0.004148	0.651629
P22	0.000019	0.301758	0.698224	0.003125	0.280771	0.716104	0.003969	0.238952	0.757079
P23	0.019307	0.262913	0.717780	0.011202	0.357004	0.631795	0.037131	0.093783	0.869086
P24	0.381204	0.000138	0.618658	0.346990	0.005155	0.647856	0.244312	0.037252	0.758436
P25	0.051144	0.125043	0.823813	0.328949	0.004509	0.666543	0.059213	0.139097	0.801690
P26	0.011331	0.000414	0.988255	0.000000	0.007939	0.992061	0.000000	0.003499	0.996501

The average value of mean-square error, obtained as a part of a calibration process, equals 0.49 m of water (variation range of 0.01–3.6738) and corresponds to conventional standards of fitting of hydraulic models of water pipeline networks (absolute error is less than 2.5 meters of water).

Since similar results of the analysis of the Theil statistics were obtained for flow in model links, the described hydraulic model of Cracow WSS can be regarded as a good simulating model.

5. CONCLUSION

The examinations described in the paper show that the Theil statistics are very useful and accurate in the calibration of hydraulic parameters such as the pressure and velocity of flow. It is worth emphasising that the Theil inconsistency statistics are easy in application and at the same time clear when it comes to the interpretation of possible calibration errors.

The model of the Cracow WSS the operating parameters of which were calibrated in 2006 was verified under extreme operation conditions in 2007. This simulation included minimal and maximal capacities of 4^{th} July (138 600m^3/d) and 2^{nd} July (155 388 m^3/d). The obtained results of the Theil statistics prove that the hydraulic model is very good and perfectly fitting to be used in the real water supply system.

The calibrated hydraulic model of Cracow forms the basis for the construction of the dynamic quality model. The aim of the quality software packet of EPANET is to forecast water quality variations during transport to consumers under changeable hydraulic conditions of water supply system operation.

The worked out and calibrated hydraulic model of water supply system of Cracow is now a useful analytical tool helpful in the management of the operation and development of the water distribution and production system. The computer analysis of water supply system operation gives the possibility of taking the most effective steps that minimize the results of unexpected random events appearing during its work. Such model can be useful in taking decisions concerning the modernization and development range of this system.

REFERENCES

[1] DENCZEW S., *Zmodyfikowana postać systemu eksploatacji sieci wodociągowych i kanalizacyjnych*, Mat. Konf., II Kongres Inżynierii Środowiska, Monografie PWN, Vol. 32, Lublin, 2005, 365–372.

[2] DENCZEW S., KRÓLIKOWSKI A., *Podstawy nowoczesnej eksploatacji układów wodociągowych i kanalizacyjnych*, Arkady, Warsaw, 2002.

[3] HOTLOŚ H., *Metodyka i przykłady prognozowania kosztów naprawy przewodów wodociągowych*, Ochrona Środowiska, 2006, Vol. 28, No. 1, 49–54.

[4] RAK J., PIETRUCHA K., *Some factors of crisis management in water supply system*, Environment Protection Engineering, 2008, Vol. 34, No. 2, 57–66.
[5] CIEŻAK W., SIWOŃ Z., CIEŻAK J., *Modelowanie poboru wody w osiedlach mieszkaniowych*, Ochrona Środowiska, 2008, Vol. 30, No. 2, 23–28.
[6] TCHÓRZEWSKA-CIESLAK B., *Water supply system reliability management*, Environment Protection Engineering, 2009, Vol. 35, No. 2, 29–35.
[7] ZIMOCH I., JAMER M., BINDA B., *Eksploatacja systemu dystrybucji wody we Wrocławiu w aspekcie awaryjności sieci wodociągowej*, Ochrona Środowiska, 2005, Vol. 27, No. 3, 65–68.
[8] ZIMOCH I., *Zastosowanie modelu komputerowego do wspomagania procesu eksploatacji systemu wodociągowego*, Ochrona Środowiska, 2008, Vol. 30, No. 3, 31–35.
[9] BERGEL T., PAWEŁEK J., *Quantitative and economical aspects of water loss in water pipe network in rural areas*, Environment Protection Engineering, 2008, Vol. 30. No. 3, 59–64.
[10] HOTLOŚ H., *Analiza uszkodzeń i kosztów napraw przewodów wodociągowych w okresie zimowym*, Ochrona Środowiska, 2009, Vol. 31, No. 2, 41–48.
[11] KASPERSKA E., *Dynamika systemowa, symulacja i optymalizacja*, Wydawnictwo Politechniki Śląskiej, Gliwice, 2005, 136–140.
[12] ZIMOCH I., *Reliability analysis of water supply system in the aspect of water production subsystem's failure*, Polish Journal of Environmental Studies, 2007, Vol. 16, No. 2A, part III, 815–819.
[13] ZIMOCH I., *The Krakow's water supply system operation in the aspect of water distribution subsystem failures*, Proc. of Conference on Water Observation and Information System for Decision Support, Balwois, 2006, p. 160.
[14] ZIMOCH I., *Determination of reliability operation model of water supply system* (*WSS*) *in the aspect of secondary water contamination in a water pipe network*, the final report of research on KBN project No. 5T07E 044 25, Gliwice, 2007.
[15] BOULOS P.F. et al., *Comprehensive Water Distribution Systems Analysis Handbook for Engineers and Planners*, MWH Soft, Inc. Pasadena, CA., 2004.
[16] DUZINKIEWICZ K., DRDYS M.A., CHANG T., *Hierarchical Model of Predictive Control of Integrated Quality and Quantity in Drinking Water Distribution Systems*, Urban Water Journal, 2005, No. 6, 27–30.
[17] GRECO M., del GIUDICE G., *New Approach to Water Distribution Network Calibration*, Journal of Hydraulic Eng., 1999, Vol. 125, No. 8, 295–308.
[18] KNAPIK K. et al., *Metody oceny niezawodności podsystemu dystrybucji wody*, Monografie PAN, 2001, Vol. 2.
[19] LANSEY K.E. et al., *Calibration assessment and data calibration for water distribution network*, Journal of Hydraulic Eng., 2001, Vol. 127, No. 4, 58–61.
[20] LSROCK B.E., JEPPSON R.W., WATTERS G.Z., *Hydraulics of Pipeline Systems*, London, New York, Washington D.C., CRC Press, Boca Raton, 2000.
[21] NITIVATTANANON V., SADOWSKI E.C., QUIMPO R.G., *Optimization of water supply system operation*, Journal of Water Research Planning and Management ASCE, 1996, 122(5), 374–384.
[22] SIWOŃ Z. et al., *Użytkowanie metody bieżącego prognozowania krótkotrwałego poboru wody w systemach wodociągowych*, Conference materials: Zaopatrzenie w wodę, jakość i ochrona wód, PZITS, Poznań, 2006, 119–155.
[23] WALSKI T.M., CHASE D.V., SAVIC D.A., *Water Distribution Modelling*, Haested Press, Waterbury, CT, USA, 2001.
[24] ROSSMAN L.A., *EPANET 2 Users Manual*, Cincinnati, U.S. Environmental Protection Agency, 2000.
[25] SIWOŃ Z. et al., *Badania układów przesyłu i dystrybucji wody na terenie Wrocławia*, Część I. *Badania rurociągów przesyłowych oraz magistralnej sieci wodociągowej w południowych i zachodnich rejonach Wrocławia*, Część II. *Badania sieci wodociągowej na terenie Leśnicy, Psiego Pola, Zakrzowa, Pawłowic i zachodnich rejonów Wrocławia*, Raporty Instytutu Inżynierii Ochrony Środowiska, Wrocław 1994, 1995, 1996.