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Reducing Uncertainty of Infrastructure Leakage Index – A Case Study

B. Babić[a,]*, M. Stanić[a], D. Prodanović[a], B. Džodanović[b], A. Đukić[c]

[a]*University of Belgrade, Faculty of Civil Engineering, Bul. Kralja Aleksandra 73, 11000 Belgrade, Serbia*
[b]*Ehting, Vele Nigrinove 16/1, 11000 Belgrade, Serbia*
[c]*Institute for the Development of Water Resources "Jaroslav Cerni", Jaroslava Cernog 80, 11226, Belgrade, Serbia*

Abstract

In water distribution systems (WDS) of developing countries, data about assets and consumption have great uncertainty. That uncertainty propagates to the performance indicators (PIs), leading to possible incorrect management decisions. To reduce the PI's uncertainty, it is necessary to analyze and reduce errors of each input variable. This paper presents methodology, based on a set of activities, to reduce the uncertainty of water balance components and Infrastructure Leakage Index. The method is tested on the WDS of Požarevac (Serbia) city. The example demonstrates how execution of activities reduced the indicator's uncertainty, although the overall indicator's value wasn't continuously improving.

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Keywords: Water distribution systems; performance indicators; PI; uncertainty; ILI.

1. Introduction

The accuracy and uncertainty of the water balance components estimation, as well as of the performance indicators (PI), in water distribution systems (WDS) depends on the accuracy and uncertainty of the input (measured) data. Since data with great uncertainty may lead to inaccurate and wrong conclusions and thus to incorrect management decisions, there is a need to evaluate the quality of the input data in terms of reliability of data source and accuracy of measurement. Moreover, the main idea presented in this paper is to emphasize importance of reducing uncertainty of PIs, before taking any steps on improving their values. This management practice is especially important in developing countries, where WDS network data and measurements are very scarce and unreliable.

* *Corresponding author.* Tel.: +381 11 32 18 558; fax: +381 11 33 70 223
E-mail address: babic@grf.bg.ac.rs

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Every measurement, no matter how carefully performed, have certain amount of uncertainty. It is necessary to quantify these uncertainties and based on their obtained values, take measures for their minimization. The measured uncertainty is defined as a parameter associated with the result of the measurement that characterizes the dispersion of results [1] and should be recorded as metadata. This uncertainty is propagated in further calculations to the estimated values of PI [2, 3]. Assuming that errors are random and normally distributed, uncertainty can be expressed through corresponding standard deviation (σ). Common measure of uncertainty (Δ) in practice corresponds to the confidence interval of around 95%, meaning that Δ is 2σ. For calculation of the performance indicators, various input variables are used. It is clear that none of the data (variable) cannot be regarded as accurate, they are just the "*best estimate*" to a greater or lesser extent. Often variable φ is measured indirectly by measuring other variables $X_1,\ldots, X_N$, or calculated via the function $\varphi = f(X_1,\ldots, X_N)$. In such cases, the rules for the propagation of uncertainty are applied to determine the uncertainty of φ ($\Delta\varphi$). For example, accuracy of the estimated value of non-revenue water (*NRW*) depends on the accuracy of the measured system input volume and revenue water. The ISO methodology [1] for determining the propagation of uncertainty has been accepted as a standard method for the evaluation of uncertainty of measurement. The ISO methodology has been successfully applied in water distribution systems, for expressing uncertainty in measurements in order to evaluate uncertainty on the water balance calculation [4]. It is also used for assessing the impact of uncertainty of the input variables on the estimated values of PI [5].

In this paper method for reducing uncertainty of the water balance components and the *ILI* index is presented. The methodology is applied to the WDS in the city of Požarevac (Central Serbia). The example demonstrates how execution of activities reduced the indicator's uncertainty, although the overall indicator's value wasn't continuously improving.

2. The method for reducing the uncertainty of ILI

2.1. Calculation of the value of ILI and its uncertainty

Physical water losses from the WDS is impossible to completely eliminate, thus IWA proposed an equation to determine the Unavoidable Annual Real Losses (*UARL*)

$$UARL = (18 \cdot L_m + 0{,}8 \cdot N_{conn} + 25 \cdot L_{conn}) \cdot P \tag{1}$$

Where: *UARL* - unavoidable annual real losses of water (l/day), L_m - the total length of the distribution network (km), N_{conn} - the number of service connections, L_{conn} – the length of the service connections pipes from the connection to the water supply pipe to the water meter (km), P - the average operating pressure in the system (m).

The analysis of the water balance, among other things, determines the value of real water losses in the observed period (Current Annual Real Losses - *CARL*). The performance indicator Infrastructure Leakage Index (*ILI*) has been introduced (Equation 2) to compare the overall performance management of real water losses [2]:

$$ILI = \frac{CARL}{UARL} \tag{2}$$

The measurement inaccuracies and errors due to data handling procedures in the WDS is further propagated to the estimated values of the water balance components and *ILI* indicator. Applying the ISO methodology for determining the propagation of uncertainty, user can determine the uncertainty of the water balance components and *ILI*. According to the ISO methodology, the equations for calculating uncertainty of some important indicators are presented below:

- The uncertainty of input volume (ΔV_{inp}), that goes into the WDS from the n_i water source ($\Sigma V_{inp,i}$) is:

$$\Delta V_{inp} = \frac{\sqrt{\sum_{i=1}^{n_i}\left(V_{inp,i}\Delta V_{inp,i}\right)^2}}{\sum_{i=1}^{n_i} V_{inp,i}} \tag{3}$$

- The total volume of *NRW* is:

$$NRW = \sum_{i=1}^{n_i} V_{inp,i} - \left(\sum_{i=1}^{n_{BMAC}} V_{BMAC,i} + \sum_{i=1}^{n_{BUMC}} V_{BUMC,i}\right) \tag{4}$$

and its uncertainty:

$$\Delta NRW = \frac{\sqrt{\sum_{i=1}^{n_i}\left(V_{inp,i}\Delta V_{inp,i}\right)^2 + \sum_{i=1}^{n_{BMAC}}\left(V_{BMAC,i}\Delta V_{BMAC,i}\right)^2 + \sum_{i=1}^{n_{BUMC}}\left(V_{BUMC,i}\Delta V_{BUMC,i}\right)^2}}{NRW} \tag{5}$$

- The uncertainty of the *UARL*, expressed in l/day (Eq. 3), is:

$$\Delta UARL = \sqrt{\frac{\left(18L_m\Delta L_m\right)^2 + \left(0,8N_{conn}\Delta N_{conn}\right)^2 + \left(25L_{conn}\Delta L_{conn}\right)^2}{\left(18L_m + 0,8N_{conn} + 25L_{conn}\right)^2} + \Delta P_{aver}} \tag{6}$$

- The uncertainty of performance indicator *Op29 (ILI)* is:

$$\Delta Op29 = \Delta ILI = \sqrt{\left(\Delta CARL\right)^2 + \left(\Delta UARL\right)^2} \tag{7}$$

where $V_{inp,i}$ - the input volume from the WDS source (m^3) and $\Delta V_{inp,i}$ - 95% confidence limit (CL), $V_{BMAC,i.}$ – the billed and metered authorized (legal) water consumption (m^3) and $\Delta V_{BMAC,i.}$ - 95% CL, $V_{BUMC.,i}$ - billed unmetered authorized (legal) water consumption (m^3) and ΔV_{UAC} - 95% CL, n_{BMAC} and n_{BUMC} - total number of consumer catogories, V_{AC} - authorized (illegal) unbilled water consumption (m^3) and ΔV_{UAC} - 95% CL, V_{AC} – the total billed authorized (legal) water consumption (m^3) and ΔV_{AC} - 95% CL, V_{UC} - unauthorized (illegal) water consumption (m^3) and ΔV_{UC} - 95% CL, V_{CME} - water volume due to errors on the water meters (m^3) and ΔV_{CME} - 95% CL, L_m – the length of the main pipes (km) and ΔL_m - 95% CL, N_{conn} - the number of service connections (-) and ΔN_{conn} - 95% CL, L_{conn} - the length of the service connection pipes (km) and ΔL_{conn} - 95% CL, P_{aver} - the average operating pressure in the WDS (m) and ΔP_{aver} - 95 % CL.

2.2. Methodology for the reduction of uncertainty of the water balance components and ILI

Presented methodology proposes steps, or sets of activities that should be carried out in order to have more reliable estimate of the water balance components and *ILI*. After each step, uncertainty will be recalculated and reduced, and it will be shown that even though *ILI* could be worsen, reliability of estimate will constantly improve. The main idea behind this methodology is that it does not make any sense to improve PIs, before it can be reliably estimated. Even though this can be viewed as a common sense, WDS in developing countries, that usually have a problem with excessive leakage (high values of *ILI*), are tempted to apply measures for reduction of *ILI*, before they are able to have a reliable estimate. This can be signed as a “worse management practice”, simple because management decisions are trials and errors, with results that cannot be validated.

Fig. 1 schematically shows the influence of certain steps (that will be explained in detail in the following text) on the reduction of the uncertainty of *ILI*. Again, it should be noted that steps will only improve the reliability of PI, and not necessarily its value.

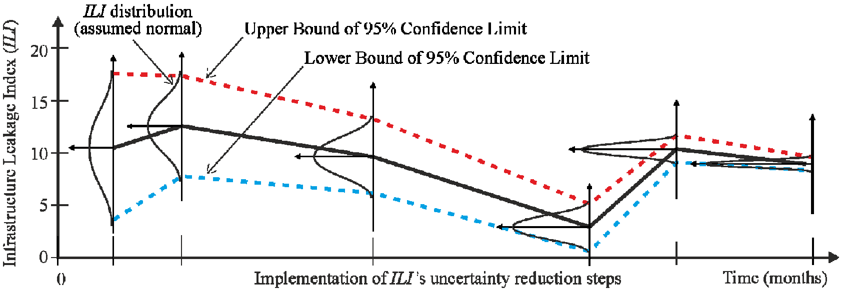

Fig. 1. Change of the *ILI* index after implementation of steps for reduction of uncertainty

In the initial step of proposed methodology, the available data on the WDS are analyzed, including the data on pipes, facilities, consumers, water consumption, existing databases, measurements, etc. Based on existing data, components of the water balance and PI, as well as the uncertainties of the input data and their propagation are calculated. After, initial step, the following steps are necessary to carry out:

Step 1: Installation of high reliability flow meters at all water sources of the WDS, if these do not already exist. If they exist, they should be either calibrated or the replacement with meters of greater accuracy should be considered. Since the input volume of the supplied water has the highest value of all the components of the water balance, it is of utmost importance that the main flow meter accuracy is high, and the uncertainty of measured volume is as small as possible (e.g. less than ±2%, to a confidence interval of 95%). Due to the propagation of uncertainty, a greater value results in a negative impact on the reliability of further calculations. Where several water sources with flow meters exist, assuming that each flow meter registers similar water volume, the total uncertainty of input volume is reduced, as shown in Fig. 2 [6]. If there are more flow meters and each registers different volume of water and have a different uncertainty, the meter that have the highest value of metered volume multiplied by percent of uncertainty should have first priority for replacement or calibration.

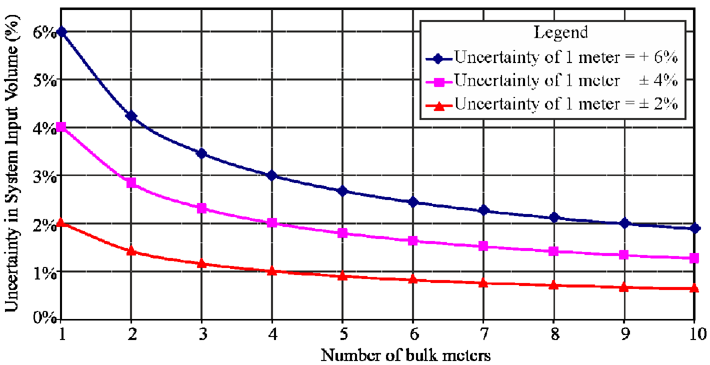

Fig. 2. Uncertainty of System Input Volume, assuming all register equal volumes [6]

Step 2: Designing of the GIS and database of WDS facilities, water consumers, including the water billing software.

Step 3: Recording and locating all consumers and entry into the water consumption database and the GIS, for those consumers whose consumption is metered as well as for consumers whose water consumption is billed on a lump sum basis. In almost all WDSs determining the volume of authorized billed water consumption is usually the second largest source of errors or uncertainty, immediately after the system input volume measurements. To reduce the uncertainty of this component it is necessary to establish a reliable database of consumers and consumption (billing), or to analyze, and if necessary, improve the existing database with all necessary records on consumers and consumption, and enter the data into the GIS. During fieldwork, it is also possible to detect unauthorized (illegal) consumers, faulty water meters and unauthorized water meter tampering.

Step 4: Water meter reading over a period of at least one year and entry of metered water consumption data into the database, the analysis of consumption of all consumer categories. At this stage, it is recommended to conduct an assessment of the accuracy of the consumers' water meters, for different categories, which can be performed on a statistical sample of water meters. Non-registration of small flows is the third largest source of errors and in developed countries, in well managed WDSs, the recommended default value of +/-2% of the actual volume that has passed through the meter (not 2% of the registered volume) for these apparent losses [6].

Step 5: Detection and identification of all WDS elements (diameter, length and type of pipe material, length of service connection pipes) and the entering of such data into the GIS.

Step 6: The establishment of a mathematical model using a software package for WDS modeling, which preferably has a connection with the consumer database and the GIS. The nodal water consumption of all categories of consumers on an average annual level is entered in the mathematical model. Defining flow and pressure measuring points within the WDS for the purpose of model calibration, establishment of measuring points, performing of measurements and calibration of the mathematical model. The operation of the WDS is analyzed on the calibrated mathematical model. Throughout implementation of steps 1-6, the propagation of the uncertainty of the input data is also performed, and the uncertainty of components of the water balance and PI is recalculated.

3. Case study – Požarevac WDS

3.1. Description of the Požarevac WDS

The Požarevac WDS (Central Serbia) supplies water to about 50,000 residents, public institutions and commercial consumers. Towards the end of 2008 a comprehensive project for the reconstruction and improvement of the efficiency of the water supply of the city of Požarevac was initiated. The project was the implementation of a program to increase the efficiency of the water supply services, including the reduction of water losses. The entire project was implemented in the 2008-2013 period [7, 8].

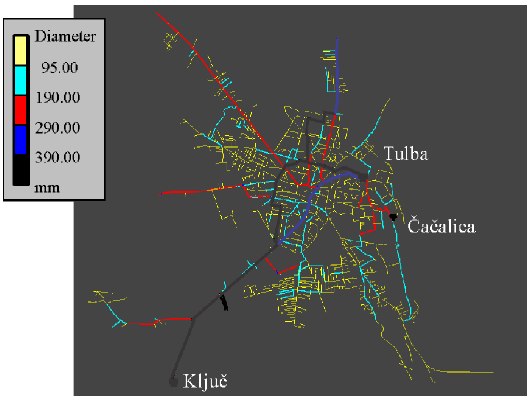

Fig. 3. The Požarevac WDS

Water is provided by groundwater abstraction from the nearby source of Ključ. Water from the wells is supplied to the water tank at the source (having volume of 2 x 2500 m^3), from where pumping station Ključ delivers water through Ø600 pipe to the city and the Tulba water tank. On Ø600 pipe old electromagnetic flow meter was replaced with a new one during the course of the project. From Tulba tank, water is pumped to a reservoir Čačalica. Within Čačalica there is booster pump (Fig. 3).

At the beginning of the project, based on the data available from PUC "Waterworks and Sewerage" Požarevac, the total water input volume to the WDS in 2008 was estimated to be around 6.54 million m3/year (an average of 207.4 l/s). The total billed water consumption was about 3.93 million m^3/year (124.6 l/s), and households (residential houses and residential buildings) accounted for 64.3% of the total consumption (residential houses 46.9% and residential buildings 17.4%). The average number of monthly water bills (invoices) in the same year was about 12,400, of which 10% is for industry and 90% for households (45% residential houses and 45% residential buildings).

Data on illegal consumers were not available, only rough estimates existed. Data on the total length of the water supply pipelines was unreliable: the Master Plan of Požarevac assumes about 100 km of distribution pipelines, while the internal data of the public utility company (PUC) pointed to a higher estimated length of pipelines, from 130 to 150 km. According to available information in that time, the most common pipe materials used were asbestos cement (53.5%) and plastics (35.0%).

3.2. Results

Based on the data available at the beginning of the project (data for year 2008), components of the water balance and the value of *ILI* were calculated, as well as their uncertainty (Table 1). Estimated *UARL* amounted to 231,100 m^3/year, with ±29.6% uncertainty, and at the end of the Project estimated *UARL* is 263,700 m^3/year ±5.5%. The results had great uncertainty, at the start of the Project, and were not usable for rendering proper management decisions. Table 1 presents the results obtained after subsequent implementation of activities throughout the Project. The average operating pressure in the WDS is taken from calibrated mathematical model. The results indicate a higher reliability of the calculated components of the water balance and the *ILI* index. For example, the total length of the water supply network has increased from (unreliable) 140 km to 175 km (Table 1). The pipes are plastic (PE100, PE80 and PVC) with total length of 99 km (56.4%) and asbestos cement with total length of 55.5 km (31.7%). Pipes with a diameter of less than 100 mm were 112.8 km in total length (64.5%). It is also interesting that the average number of monthly bills increased to about 17,730 bills, of which 10% is for industry and 90% for households (54% residential houses and 36% residential buildings). It should be noted that no assessment of accuracy of different categories of consumer water meters was conducted on the statistical sample of meters, but after replacement of worn-out water meters with new ones of higher accuracy, it was observed that the metered water amounts increase up to 20% on new meters, comparing to the amounts metered before meter replacement.

4. Discussion

From the above results, it can be seen that the uncertainty of the input data was extremely high at the beginning of the project, contributing to high uncertainties of the estimated values of the water balance components and the *ILI* index. The largest source of error, or uncertainty, was measured input volume (inflow). Hence, increased reliability of measurements for water inflow was a priority, since the Požarevac WDS is supplied only from one source. Installation of only one higher accuracy flow meter decreased the uncertainty for the non-revenue volume from 54% to 22% and for the *ILI* from 88% to 49%.

After activities related to the reduction of uncertainty of data on water consumption in the WDS were carried out, the uncertainty of NRW was reduced to ± 4.6%, but the uncertainty of the *ILI* index was still high, around ± 30.5%. Then, after the reduction of uncertainty of the data on physical properties of the WDS, the uncertainty of NRW remained the same, while the uncertainty of the *ILI* index decreased to 21.4%. Finally, after calibration of the mathematical model and pressure control in certain zones, the uncertainty of the average operating pressure in the WDS was reduced and the *ILI* index had an acceptable uncertainty of ± 9%.

Table 1. Estimated values of the components of the water balance and *ILI* throughout the Project

	Beginning of the Project		After the Implementation of Steps 1, 2, 3 and 4		After the Implementation of Steps 1, 2, 3, 4 and 5		End of the Project	
Input data	The best estimated value	95% confidence interval (±)	The best estimated value	95% confidence interval (±)	The best estimated value	95% confidence interval (±)	The best estimated value	95% confidence interval (±)
System input volume - input from the source (m^3/yr) - V_{inp}	6,539,440	20%	6,690,000	2%	6,690,000	2%	6,690,000	2%
Billed metered legal water consumption (m^3/yr) - $V_{BMAC,i.}$	3,741,978	20%	3,351,314	2%	3,351,314	2%	3,351,314	2%
Billed unmetered legal water consumption (m^3/yr) - $V_{BUMC,i}$ - (5 % of $V_{BMAC,i.}$)	196,454	50%	167,566	20%	167,566	20%	167,566	20%
Unbilled legal water consumption (m^3/yr) - V_{UAC} - (5 % of V_{inp})	326,972	80%	66,900	80%	66,900	80%	66,900	80%
Total billed legal water consumption (m^3/yr) - V_{BAC} (*RW*)	3,929,075	*estimated as* 14%	3,518,879	*estimated* as 1,6%	3,518,879	*estimated as* 1,6%	3,518,879	*estimated as* 1,6%
Illegal water consumption (m^3/yr) - V_{UC} - (2% of V_{inp})	130,789	80%	6,690	80%	6,690	80%	6,690	80%
Volume of water due to errors on water meters (m^3/yr) - V_{CME} - (10 % of $V_{BMAC,i.}$)	374,198	50%	335,131	50%	335,131	50%	335,131	50%
Length of the main pipes (km) - L_m	140	30%	140	30%	175	1%	175	1%
Number of service connections (-) - N_{conn}	11,000	30%	13,190	2%	13,190	2%	13,190	2%
Length of service connection pipes (km) - L_{conn}	110	50%	110	50%	131.9	10%	131.9	10%
Average operating pressure in the WDS (m) - P_{aver}	45	20%	45	20%	45	20%	42.5	5%
Non Revenue Water (m^3/yr)	2,610,365	54.4%	3,171,120	4.6%	3,171,120	4.6%	3,171,120	4.6%
ILI	7.7	87.0%	12.0	30.5%	9.9	21.4%	10.5	9.1%

From the results obtained after application of activities from Steps from 1 to 6, it can be concluded that pinpointing of all consumers and their entry into a GIS database led to a significant reduction of uncertainty. By establishing a new database the number of monthly invoices were significantly increased (by almost 50%), as well as the number of registered water-meters (by about 20%). However, the volume of billed water consumption was reduced by approximately 10%. The reason for the reduction in the volume of billed water lies in external factors that could not be influenced by the project: an increase in water prices and the economic crisis that started at the end of 2008, which resulted in a significant reduction in the volume of billed water, especially for commercial users (for about 22%).

Records of all the WDS facilities significantly contributed to increasing the reliability of the pipe length data. From the results it can be concluded that the PUC before the project did not possess reliable information on the length of pipes with a diameter of less than 100 mm. Also, the project activities significantly change the data on pipe materials.

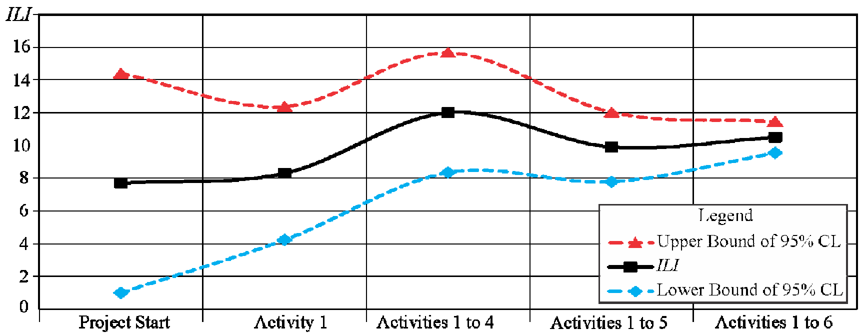

Fig. 4. Impact of implemented activities to change the value of ILI and its uncertainty (data for WDS Požarevac)

Since no accuracy assessment of water-meters was conducted, a large uncertainty of the apparent water losses still remains. In the future, activities should be conducted to improve their reliability. Calibration of the mathematical model was successfully implemented, enabling the reliable determination of the average operating pressure in the WDS. This is of particular importance since the *UARL* value is directly proportional to average pressure. In this way, the uncertainty of the *ILI* index is reduced as well. Implementation of all activities led to the increase of the estimated value of the *ILI* indicator from 7.7 to 10.5, but with significant reduction in its uncertainty from 88% to 9%. Fig. 4 presents the impact of all implemented activities to changes in the value and uncertainty of *ILI* for Požarevac WDS.

5. Conclusion

In many water systems, especially in developing countries, data on the elements of the water supply and distribution system, measurements of flow and water consumption have significant uncertainties. Data of great uncertainty may lead to incorrect conclusions and wrong management decisions. Quantification of uncertainties enables the water company to determine priorities where the activities for its improvement need to be focused. Proposed methodology, implemented on WDS of the city Požarevac, shows how implementation of appropriate activities can reduce the uncertainty of the estimation of the components of the water balance and performance indicators, thus providing conditions for improvement of PIs.

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References

[1] ISO/IEC Guide 98-3:2008. Uncertainty of measurement Part 3: Guide to the expression of uncertainty in measurement (GUM:1995), 2008.
[2] H. Alegre, J.M. Baptista, E. Cabrera, F. Cubillo, P. Duarte, W. Hirner, W. Merkel, R. Parena, Performance Indicators for Water Supply Services. - Second Edition, Manual of Best Practice, IWA Publishing, London, UK, 2006.
[3] J. Thornton, R. Sturm, G. Kunkel, Water Loss Control, McGraw-Hill, New York, 2008.
[4] J. Sattary, D. Boam, W.A. Judeh, and S. Warren, The Impact of Measurement Uncertainty on the Water Balance, Water and Environment J., 16(3) (2002) 218-222.
[5] M. Herrero, E. Cabrera Jr., F.J. Valero, A New Approach to Assess Performance Indicators' Data Quality. Pumps, Electromechanical Devices and Systems Applied to Urban Water Management Systems, E. Cabrera and E. Cabrera Jr., eds., Swets & Zeitlinger, Lisse, The Netherlands, 2003, pp. 69-78.
[6] A. Lambert, R. Taylor, Water Loss Guidelines, Prepared for: Water New Zealand, 2010.
[7] PUC "Waterworks and Sewerage" Požarevac , The Annual Report on Billed Water Quantities (In Serbian), 2013.
[8] Ehting, Program to Improve Efficiency and Water Loss in Water System of City Požarevac – Serbia (In Serbian), 2013.