AVERAGE OPERATING PRESSURE EFFECT ON WATER SUPPLY SYSTEMS PERFORMANCES. A CASE STUDY FOR 12 ROMANIAN SMALL WATER DISTRIBUTION NETWORKS

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ABSTRACT:

The performance evaluation of an implemented water distribution network is in tight relation with the choice of adequate measures for water loss reduction. Hence, the consequences of placing the water network in a wrong performance category are bad and will conduct to unreasonably costs or considerable water loss volumes. Therefore, the evaluation of the water network performance level based on both Non-Revenue Water (NRW) and Infrastructure Leakage Index (ILI) indicators is to be recommended. This paper deals with the performance evaluation of water distribution systems based on the calculated performance indicators NRW and ILI. For this purpose, collected data for a period of one year from 12 Romanian small water distribution systems and two simplified average pressure determination methods were used.

1. INTRODUCTION

The performance of the water supply systems can be established by analysing the water balance and two major performance indicators - Non-Revenue Water (NRW) and Infrastructure Leakage Index (ILI). The water balance is referring to the water loss; it is an important aspect of any water supply system and it represents the difference between the water volumes measured at the input and at the output of a system. NRW indicator represents a well-known performance indicator at national and global level for an efficient analysis of the water distribution systems. ILI indicator implies data regarding the hydraulic and geometrical characteristics of the studied water network such as: the network length, the number of the services connections and their length and the average pressure within the network. These important factors are further detailed for a better and appropriate understanding of the discussed subject.

1.1 Water balance

Based on the best practices gathered from many countries, International Water Association (IWA) has designed and produced a standard approach for Water Balance calculations with definitions of all terms involved (IWA, 2020), (Pilcher R. et al., 2007).

According to IWA methodology and the Romanian norm NP133/2013 (NP 133, 2013) for new or employed water networks a calculation of a Water Balance is imposed.

Hence, the components of a water balance are (see table 1):

- system input water volume; it represents the water volume that flows in the water distribution network;
- authorised consumption; it represents the metered and/or unmetered water consumption taken from the connected consumers;
- water losses; it represents the difference between the system input volume and the authorized consumption. It consists of 2 parts: the apparent losses and the real losses. The water loss volume is equally influenced by the apparent losses and by the real losses (Rfosa J.C. et al., 2014);
- unbilled authorized consumption; it represents the annual unmetered water volume to supply the fire extinguishers, the public drinking fountains etc.;
- NRW; it represents the apparent and real losses and the unbilled authorized consumption. Also, as it can be seen in table 1, the NRW can be calculated by using the following relation:

$$NRW = SIV - RW$$

So, when inaccurate volumes are introduced in the calculation of the NRW, problems can occur (Handbook, 2010). Therefore, precisely volumes of the billed water will improve the precision of the NRW calculus. Usually, a water audit allows the Water Operators to identify and to quantify the consumed water volume and the water losses volumes.

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SYSTEM INPUT VOLUME (SIV)	AUTHORISED CONSUMPTION	BILLED AUTHORISED CONSUMPTION	BILLED METERED CONSUMPTION	REVENUE WATER (RW)
			BILLED UNMETERED CONSUMPTION	
	WATER LOSSES	UNBILLED AUTHORISED CONSUMPTION	UNBILLED METERED CONSUMPTION	NON REVENUE WATER (NRW)
			UNBILLED UNMETERED CONSUMPTION	
		APPARENT LOSSES	UNAUTHORISED CONSUMPTION	
			CONSUMER METER INACCURACIES	
	REAL LOSSES		LEAKAGE ON TRANSMISSION AND DISTRIBUTION MAINS	
			LEAKAGE AND OVERFLOW AT STORAGE TANKS	
			LEAKAGE ON SERVICE CONNECTIONS UP TO POINT OF CONSUMER METER	

Table 1. Water Balance (IWA, 2020)

In Romania, the water losses vary from 15 to 53 % of the system input volume, a relative high percent in ratio with other European countries where the maximum percent is no greater than 25% (France). Nevertheless, this range is smaller than in case of Bulgaria, where the water losses exceed 60% (AVK NRW, 2017).

1.1 Performance indicators

It is important to mention that for any Regional Water Operator, the most important performance indicator is the billed metered consumption therefore the revenue water. However the water losses are not to be neglected when the performance of a water network is established.

Usually, the performance indicators are calculated with the elements provided by the Water Balance according to IWA (Hamilton S., McKenzie R., Seago C., 2009).

a) NRW (Non-Revenue Water) performance indicator, in %

This indicator represents the percent of the system input water volume that brings no revenue. According to this percent, a

water distribution network can be integrated into a specific performance category (as table 2 emphasis).

b) CARL (Current Annual Real Losses) performance indicator, in m³/year

CARL indicator implies knowledge of the real losses and it can be calculated with the one of the two following relations (Lenzi C., Fortini M., 2014):

- litres/day

$$CARL = \frac{Real\ losses \cdot 1000}{T_p} \quad (1)$$

or

- litres/day/service connection

$$CARL = \frac{Real\ losses \cdot 1000}{T_p \cdot N_c} \quad (2)$$

where: T_p is the number of days in which the Water Distribution Network (WDN) is pressurized over the period of water balance calculation;

N_c - the number of service connections.

Category	NRW, (%)	Performance category (P.C.)	
1-C1	0-10	very good	Optimal situation according to the relevant indicator
2-C2	10-20	good	Low level of risk according to the relevant indicator Additional measures to improve the indicator are not necessary.
3-C3	20-30	average	Average value of the relevant indicator. Additional measures to improve the indicator are not necessary except a good planning in order to identify the potential failures
4-C4	30-40	critical	Critical value of the relevant indicator. This category represents the trigger to initiate the corrective actions to improve the indicator.
5-C5	40-40 ⁺	unacceptable	Unacceptable state that demands fast actions to improve the performance of the relevant indicator. It is an indicator that confirms that early retrospective actions should be done

Table 2 .Water distribution system performance based on NRW values

c) UARL (Unavoidable Annual Real Losses) performance indicator, in m³/year

UARL indicator represents the minimum theoretical level of the water losses.

In the national (*** Hanbook, 2010) and international (Lambert A.O. and McKenzie R.D., 2002), (McKenzie R. and Seago C., 2005) technical literature, the following relations are recommended for the calculation of the UARL:

- litres/day

$$UARL = (A \cdot L_m + B \cdot N_c + C \cdot L_p) \cdot P \text{ (litres/day)} \quad (3)$$

and

- litres/day/service connection

$$UARL = (A \cdot L_m/N_c + B + C \cdot L_p/N_c) \cdot P \quad (4)$$

where: L_m is the network length in km;

L_p - the total length of service connections (the distance between property line and customer water meter) in km;

P - the average operating pressure in meter.

A , B and C - constants. The A , B and C values mentioned in the technical literature (Winarni, W., 2009) calculated based on in-situ measurements on a water supply network are: $A = 18$, $B = 0.8$ and $C = 25$.

If the water supplied during a day is under 24 hours, the value of UARL can be reduced. The decrease is proportional with the hours of non-supplying water.

Other relations recommended by the technical literature for the determination of the UARL, but in different measurement units are (Lambert A.O. and McKenzie R.D, 2004):

- litres/ day/ service connection:

$$UARL = (18 \cdot DC + 0.8 + 25 \cdot L_p/N_c) \cdot P \quad (5)$$

- litres/ day/ service connection/ m pressure:

$$UARL = (18/DC + 0.8 + 25 \cdot L_p/N_c) \quad (6)$$

- litres/km mains/day:

$$UARL = (18 + 0.8 \cdot DC + 25 \cdot L_p/L_m) \cdot P \quad (7)$$

- litres/km mains/day/ m pressure:

$$UARL = (18 + 0.8 \cdot DC + 25 \cdot L_p/L_m) \quad (8)$$

Where: DC is the density of the service connections/km mains.

d) ILI (Infrastructure Leakage Index) performance indicator

The performance indicator ILI (Lambert, A. 1999) represents the ratio between CARL and UARL indicators as it can be seen in the following relation:

$$ILI = \frac{CARL}{UARL} \quad (9)$$

According to the recommendations given by the technical literature and the relation (7) in order to calculate ILI indicator, CARL and UARL indicators must be in the same units, namely litres/day.

Commonly, the variation range of ILI indicator starts from 1 to 30 and sometimes over 30. In function of this values, IWA indicates the performance of a water distribution network, as shown in table 3.

ID	Performance category (P.C.)	ILI values	Real loss dm ³ /conn. day for average pressure				
			10 m	20 m	30 m	40 m	50 m
1	A	1-4	<50	<100	<150	<200	<250
2	B	4-8	50-100	100-200	150-300	200-400	250-500
3	C	8-16	100-200	200-400	300-600	400-800	500-1000
4	D	>16	>200	>400	>600	>800	>1000

Table 3. Water distribution system performance based on ILI values

The information presented in table 3 designate the following aspects:

a) performance category A and ILI values 1-4: the investments to reduce the water losses will be made on technical and economical calculus and it will include: water losses prices, risk in service deployment, water energetic value and tracking costs, measurements and network fault repairs;

b) performance category B and ILI values 4-8: in order to reduce the water losses, the following solutions are recommended:

- pressure control in the network and preservation of the water pressure in quasi-constant values, regardless the hourly consumption;
- water network partitioning into district metered areas, in flows and pressure terms to facilitate the water balance;
- properly match of the flow meters regarding the measurements' precision, quality and errors;
- to identify and to control the unbilled and unauthorized water consumptions.

c) performance category C and D and ILI > 8: this category points out the degradation of the distribution network with over 40% water losses along with the risk of a poor quality and quantity services. A redesign of the distribution network become mandatory. The aims of this redesign will cover: geometrical characteristics of the network, hydraulic calculus, rehabilitation and monitoring solutions, water balance and performance indicators.

By analysing the information presented above, it clearly results the importance of an ILI value on the performance of a water network. A miscount of ILI value can lead to a wrong performance category of the water distribution network and, in consequence, to a wrong rehabilitation measures for the system in order to reduce the water losses.

Furthermore, by analysing the relations (5) and (9) it became obvious that the errors in the calculus of the ILI can be given by the system average pressure due to its presence in the UARL relation. The network lengths and the connections numbers can

be easily calculated but the water average pressure is very hard to establish due to the lack or to the absence (in some cases) of an accurate pressure monitoring system.

Therefore, this paper is focused on methods of determination of the average pressure values for water supply systems in the case of a poor monitoring system characterised by great volumes of water losses.

2. MATERIAL AND METHOD

This study is focused on 12 water supplies and distribution systems placed in a geographic region characterised by hills and plains in a Romanian county. The customers of this networks are situated in urban and rural communities.

The main components of these supply systems are: raw water source, raw water pumping facility, water treatment plant,

service pumping station, water storage tank and water distribution network. The raw water sources differ from a system to another, they are rivers, lakes or underground waters. The water storage tanks for each system are placed to a higher altitude in order to obtain a gravitational flow into the water distribution network.

The collected data for these 12 systems, for the year 2017 were in terms of:

- geometrical characteristics of the network and the numbers and lengths of the service connections;
- hydraulic characteristics: the input and output water flows;
- billed and unbilled water and water real losses.

All information are summarized in table 4.

Water Distribution Network (WDN)	Water supply (m ³ /year)	Billed water (m ³ /year)	Unbilled water (m ³ / year)	Real losses (m ³ / year)	L_m (km)	Number of service conn. (Nc) (piece)	N_c / L_m (piece/km)
WDN 1	26 966	11 596	15 370	15 022	16	233	14.56
WDN 2	5866	3631	2235	2126	2	72	36.00
WDN 3	64 089	45 222	18 867	17 456	16.63	825	49.61
WDN 4	1 684 864	1 273 978	410 886	372 449	172	4 916	28.58
WDN 5	28 460	18 159	10 301	9 702	34.81	401	11.52
WDN 6	68 738	51 851	16 887	15 277	15.84	746	47.10
WDN 7	226 487	183 500	42 987	37 560	40.56	1 701	41.94
WDN 8	357 300	264 491	92 809	85 011	31.87	2 178	68.34
WDN 9	36 842	11 749	25 093	24 686	16.16	128	7.92
WDN 10	16 421	15 909	512	352.7 1	17.81	59	3.31
WDN 11	148 755	112 781	35 974	32 731	23.88	948	39.70
WDN 12	79 620	61 584	18 036	16 384	15.07	501	33.24

Table 4. Water distribution network features

The calculus of the average pressure is a complex and almost accurate one in theory, but in reality this value can presents important modifications due to:

- the hourly variation of the water consumption during a day which is not identical for every day of a year;
- the daily variation of the water consumption during a year which is not identical for every year;
- the water consumption intensity for a distribution network area, which is in continuous changing due to multiple factors such as: highly demand in sanitary comfort, development of the domestic and public buildings, continuous rising of the water rate, replacement of the old pipe materials with the new and better ones, climate changes, etc.

In order to obtain the most precise value of the average pressure it is recommended to use the mean values of the average pressure for each network section pipes throughout a year (Renaud E. et al., 2015). To acquire these average pressure values in situ pressure monitoring of the networks is needed. In

this way, it can be gathered values for 24 hours x 365 day of the water flow and pressure in every joint of the network.

The drawback of this method is the smaller value of the ILI parameter for the water system under surveillance, because:

- UARL value is calculated with the most accurate method given by relation (5) (McKenzie R. and Seago C., 2005);
- CARL value is small, because the real water losses are reduced by a pressure control (Nourhan S. et al., 2017).

Nevertheless, an accurate monitoring of the water network gives valid information on the real pressure in every network joint. Thus, by monitoring the system it can be considered that a method of decreasing water losses is already implemented (AVK DMA, 2017). Moreover, a performance monitoring represents itself a rehabilitation solution (Liemberger R. et al., 2007) for the water network systems.

Usually, the determination of a precise average pressure by using the monitoring method commonly will involve:

- a mathematical model of the network validated by SCADA (Halkijevic I., Vouk D., Posavcic H., 2017);
- the annual consumption curve based on the recorded data from the past years and the identification of the hourly maximum values on this curve;
- the daily variation curve of the hourly consumption during a day and the identification of the maximum consumption;
- calculus of the pressure values based on the measured flows and the elaboration of the flow-pressure curve for the network (Cheung P. B., 2010);
- calculus of the mean values of the average pressure for each network section pipes throughout a year (Renaud E., 2012).

Overall, this method can give accurate results but it implies higher costs.

Therefore, in order to calculate ILI values for the water distribution networks that have not a suitable pressure monitoring system, a simple method is proposed, with good precision for the small water systems. To validate this method the obtained results are compared with the ones obtained by using the method proposed by the Manescu A., (Manescu A. and Manescu B., 2015).

Proposed method (method 1)

This method can be applied only when some pressure monitoring points are placed on the hydraulic water supply systems. Also, a flow monitoring system is required at the beginning and at the end of the water system. This will facilitate the calculation of the mean values of the average pressure for each network section pipes of the system. The pressure values will be countered at the medium hourly consumption (namely 4 P.M., 5 P.M. and 6 P.M.) and the mean value of these data will be considered as the average pressure of the system. The measured and calculated values with the method 1 are accompanied by the index 1.

Manescu method (method 2)

This method is suitable for the hydraulic systems with no pressure monitoring point settled. In this case, the average pressure value is calculated depending on the average flow, with the following equation (Manescu A. and Manescu B., 2015):

$$p_m = 0.05 \cdot q + 0.002 \cdot q^2 + 23.8 \quad (10)$$

where: p_m is average pressure in mH_2O ;
 q - average flow in (l/s).

In this case, the average flow value is calculated based on the water volumes recorded at the beginning of the water system, measured every hour, during a year. The measured and calculated values with this method are accompanied by the index 2.

3. RESULTS AND DISCUSSIONS OF THE CASE STUDY

As specified already when presenting the working material for this study, 12 urban and rural Romanian water distribution systems were taken into consideration. The aim was to establish the performance category for these systems based on the NRW

and/or ILI indicators. For that, the ILI values were calculated by applying the methods 1 and 2 (based on network average pressure) and the NRW values were calculated based on the water flow measurements.

Water flow measurements

The water flow meters were placed at every entrance of the cities and/or villages and the data was registered during 365 days (e.g. for WDN see fig.1). For each town a typically 24-hour DMA flow profile was drawn and the average hourly water flow was calculated.

Figure 1 Water balance for the WDN 1

NRW and ILI values computation

By using the water volume difference between the system input volume and the revenue water, the NRW values were calculated for each water system, in rate per cent. Then, based on the recommendation given by the table 2 with the NRW calculated values the category of performance of each system was identified.

As presented above, the calculus of ILI demands the values of CARL and UARL indicators. Thus, for each of the 12 water systems, based on the collected data, these indicators are obtained by applying the formula (2) for CARL values and (5) for UARL values. Then, the formula (9) is used to calculate the ILI values, namely ILI_1 by using method 1 and ILI_2 by using method 2. The results are indicated in the table 5.

By analysing the obtained values the following aspects can be drawn:

- the calculated values of NRW and/or ILI indicators designate for the same network, different performance category;
- for network WDN 4: the value of 3 for ILI_1 designate a performance category "A" and the value of 4.08 for ILI_2 designate a performance category "B". Therefore, this situation will lead to measures that are not suitable for the real situation because: in case of performance category "A" the reducing of the water losses is not a default objective and in the case of performance category "B" the default measures implies great unjustified financial efforts.

Average pressure computation

Method 1 – pressure measurements

The water system pressure was measured for each system, through 365 days in different points of the system at 4 p.m., 5 p.m. and 6 p.m., namely the hours that correspond to the medium hourly consumption (SR 1343-1, 2006). With these data, the average pressure, P_1 , is calculated and the obtained values are shown in table 5.

Method 2 – pressure computation

In this case, the average pressure, P_2 , is calculated by using relation (10) where the average flow values are calculated from the water flow measurements.

In terms of average pressure the results are:

- the average pressure values calculated with the method 1 and 2 are identical for WDN 1, WDN 2, WDN 5, WDN 6, WDN 9 and WDN 10 systems;
- for the rest of the WDN systems by using the method 2 the average pressure values, P_2 , are greater than in case of method 1 P_1 , and this values would lead to the following relations $UARL_1 > UARL_2$ and $ILI_1 < ILI_2$.

So, the comparative analyse shows that the average pressure values for six of WDN (WDN 1, 2, 5, 6, 9 and 10) are identical either by using the proposed method or Manescu method. For

five WDN (WDN 3, 7, 8, 11 and 12) the average pressure values are slightly different, but it does not change the position of the WDN in a specific performance category. Only for one WDN (WDN 4) the obtained performance category is different and this situation can be explained by the higher number of service connections, namely 4916 and by the total length of the network namely 172 km.

To conclude, the proposed method is suitable and it will give good results only for shorts length of the networks with a reduced number of service connections. The results were validated for networks with total length (L) under 35 km and a number of connections (Nb) under 750, networks that verify the following relation $L/Nb < 47$. Moreover, the proposed method can be used with no difficulties by any certified water service personnel.

WDN	NRW (%)	P.C. evaluation based on NRW	CARL (l/day/conn.)	Method 1				Method 2			
				P_1 (bar) measurements	$UARL_1$ (l/day/conn.)	ILI_1	P.C.	P_2 (bar) formula	$UARL_2$ (l/day/conn.)	ILI_2	P.C.
WDN 1	57	C5	177	4.38	98	1.81	A	4.38	98	1.81	A
WDN 2	38	C4	81	3.08	46.20	1.75	A	3.08	46.20	1.75	A
WDN 3	29	C3	58	4.13	56.29	1.03	A	2.39	32.57	1.78	A
WDN 4	24	C3	208	4.25	69.27	3.00	A	3.13	51.01	4.08	B
WDN 5	36	C4	66	4.25	108.91	0.61	A	4.25	108.91	0.61	A
WDN 6	25	C3	56	3.9	53.91	1.04	A	3.9	53.91	1.04	A
WDN 7	19	C2	60	4	57.17	1.05	A	2.42	34.59	1.73	A
WDN 8	26	C3	107	4.5	56.85	1.88	A	2.45	30.95	3.46	A
WDN 9	68	C5	528	4.13	135	3.91	A	4.13	135	3.91	A
WDN 10	3	C1	16.38	4.25	273.43	0.06	A	4.25	273.43	0.06	A
WDN 11	24	C3	95	4.95	71.94	1.32	A	2.4	34.88	2.72	A
WDN 12	23	C3	90	4.43	68.29	1.32	A	2.39	36.84	2.44	A

Table 5. Performance category (P.C.) evaluation of the 12 systems based on NRW and ILI with methods 1 and 2

4. CONCLUSIONS

The evaluation of a network performances can be accomplished based on NRW and/or ILI indicators, as technical literature indicates. But, the results obtained in this study show that not always the calculated values of NRW and/or ILI indicators designate the same performance category for a system.

Thus, in order to decide which of these two indicators are more relevant for a better evaluation it is necessary to compare every parameter involved in the calculation. So, in the case of NRW values the following aspects are not included in a network performance evaluation:

- the total length of the distribution network and the number of the service connections, although the most of the water losses take place at the service connections;
- the density of service connections.

In the case of ILI values, the only water losses that are taken into consideration are the real losses as it shows the relations (1) and (2).

Therefore, the performance evaluation of a system based just on ILI indicator it is not to be recommended. It results that in order to situate a distribution network into a specific performance

category it is mandatory to consider both the NRW and ILI values. However, an important factor that is not to be neglected in the performance evaluation process is the average pressure and to be more precisely the precision of its determination.

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