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OVERVIEW AND RECOMMENDATIONS FOR ANALYSIS OF WATER DISTRIBUTION SYSTEMS BASED ON PERFORMANCE INDICATORS

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ABSTRACT:

The protection of the water sources represents a topic that concerns humanity worldwide. Hence, the decrease of the water losses that occurs in water distribution networks during its overall operational lifetime, is an important issue for water operators and for researchers at theoretical and experimental level. Over the last years progresses have been made on the evaluation and analysis methods in order to eliminate the water losses. Among these methods, the evaluation of the water distribution systems, made on performance indicators by the use of the water balance, is the most current. Thus, the calculated value of each performance indicator and the analysis of these values will lead to the identification of the real problems within the water distribution system. As a result, this analysis has to be the first step in the planning phase of a new project and in the same time, it can serve as a pattern for any water distribution systems in order to decrease the water losses at lower costs.

1. INTRODUCTION

The decrease in water losses within the potable water networks is a concern not only at research level, but also at operational level. It represents one of the effective methods for protecting the water resources and yet it assures an optimal functioning of the water distribution networks (Chirica S. et al., 2018). It is estimated that 25-50% of all delivered water worldwide is lost or never invoiced due to: leakages, deteriorated infrastructure, incorrect water pressure management, inaccurate metering or billing systems, illegal connections etc. (EU-CWC Project, 2017). Moreover, the presence of the leaks involves significant costs for water operators (Marzola I. et al., 2021). Therefore, high financial investment is allocated to reduce the water losses (Al-Bulushi M.M. et al., 2018), although these actions are not justified. A balance between the reducing water losses costs and the quantity of water lost it is necessary (Suvi A. and Riku V., 2020). For this reason, a continuous analysis of the distribution system is mandatory. In this way, quick interventions with lower costs and small volumes of water lost are ensured.

Nevertheless, early detection and repairs of the potential faults that may lead to water leakages from the system (Maiolo M., et al., 2018), have an important part in reducing the Non-Revenue Water (*NRW*) value (Kiliç R., 2021). In order to achieve these purposes, an ongoing flow and pressure management (Thornton, J., and Lambert, A.O., 2005) are needed. Moreover, better results can be reached if the distribution network is divided into smaller District Metered Areas (DMAs).The outcomes of these actions are: (i) improved performance of the systems and (ii) reduced economic costs for water operators.

Usually, the performance of a water system is given by the water balance. Therefore, the quantity of Non-Revenue Water (IWA, 2020) can be assessed from this balance even for a poor monitoring water system. Based on the analysis of the input and output volumes of water for a water distribution system it results:

$$SIV - RW = NRW \quad (1)$$

where: *SIV* is System Input Volume,
RW - Revenue Water

The study of the water losses based on *NRW* value expressed as percentages of system input volume or volumes (m^3) is essential for water operators in terms of finance and it gives an overview on the state of the water distribution system, too. In the calculus of the *NRW* the geometrical characteristics of the systems are not included. Thus, for the same percent of the *NRW*, the water lost volumes are superior for the large pipe networks and slighter for small water pipes network. Normally, the estimated economic reasonable level of *NRW* indicated by the IWA is below 10% (IWA, 2020). Water distribution network audit cannot be done based only on calculated *NRW*, expressed as a percentage of system input volume with relation (1) (Liemberger R., 2010) because of its shortcomings such as dependence: on the supply time (intermittent supply) and average operating pressure, on the level of consumption and on the distribution network geometrical characteristics.

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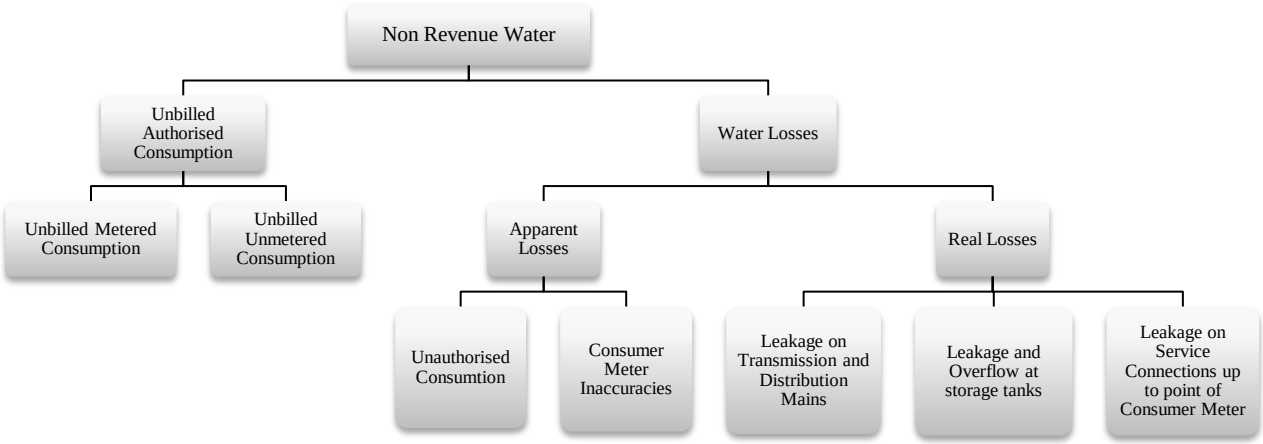


Figure 1. *NRW* components

The Non-Revenue Water is water volume that has been produced and introduced into the distribution system, but it gives no revenue because it is lost before it reaches the consumers. *NRW* includes not only the real and apparent losses (Kamani H. et al., 2012) where of the real losses have a great proportion (Fontana M. E. and Morais D., 2016) but also the unbilled authorised consumption (Liemberger R.et al., 2007). Therefore, *NRW* includes the following aspects (see figure 1) (Alegre H., 2000; IWA, 2020):

- unbilled authorised consumption:
  - unbilled metered consumption
  - unbilled unmetered consumption
- real losses that are divided into:
  - 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.

In terms of real water losses, an estimated percent of 80% to 100% is caused by water leakages from pipes (EU-CWC Project, 2017). Thus, in order to asses *NRW*, a water loss reduction strategy based on an initial specific analysis must be done.

Hence, in order to reduce water losses more effectively it becomes important to decrease the values of *NRW* components. In the absence of an accurate monitoring system the values of *NRW* components cannot be evaluated, therefore it is impossible to choose which *NRW* component must be adjusted in order to reduce its value. Therefore, for the evaluation of the water distribution system performance IWA recommends to use aside *NRW* the following performance indicators, too:

- Infrastructure Leakage Index (*ILI*) as Performance Indicator (*PI*). This indicator involves the geometrical characteristics of the network (such as length of mains, number of connections and length of connections) and hydraulic characteristics (such as pressure). Accordingly to the technical research, if the network has over 3000 service connections, *ILI* indicator gives a good estimation of the network performance (Liemberger R. and McKenzie R., 2005), but if the number of service connections is under 300 *ILI* indicator places the network into a wrong category of performance (usually in a good category that doesn't match to the real situation) (Koelbl J. And Lambert A., 2019).
- Leakage on the Network Kilometre Index (*LKN*). It gives the real technical status of the network, to be more specific the water loss for 1 km length.
- Economic Leakage Index *(ELI*). It assures the economic evaluation of the losses to the operators. *ELI* represents the actions cost to bring the water losses into the economic range. Depending on the system characteristics it can be established an economic threshold level, because further losses reduction may be inefficient.

Thus, the performance category for a water distribution network can be established based on the performance indicators values given in table 1.

Category	***NRW*** (%)		***LKN*** (m^3/yr./conn.)		***ILI***		***ELI***	
	from	to	from	to	from	to	from	to
C1	0	10	0	10000	0	10	0	1
C2	10	20	10000	20000	10	20	1	2.5
C3	20	30	20000	30000	20	30	2.5	3.0
C4	30	40	30000	40000	30	40	3.0	3.5
C5	40	40^+	40000	40000^+	40	40^+	3.5	3.5^+

Table1. Performance category of a system based on *PI* values (MMAP, 2010)

Once, the performance indicators were assessed, the technical and functional state of a water network can be classified from very good to unacceptable as follows:

- First category – C1 (very good) – Optimal state according to the relevant indicator. No further actions are necessary to improve the indicator.
- Second category – C2 (good) – Low level of risk according to the relevant indicator. No special actions are necessary to improve this indicator.
- Third category – C3 (average) – Average value of a relevant indicator. No further actions are necessary to improve the indicator besides a good management to identify possible faults.
- Four category – C4 (critical) – critical value of relevant indicator. It represents a trigger to initiate corrective actions to improve the indicator.
- Fifth category – C5 (unacceptable) – unacceptable state that demands immediate actions to improve the relevant indicator. It represents a sign that early actions should have been already taken.

In this context, the aim of this study is to assess the *NRW* and its components based mainly on IWA recommendation for an operational water network distribution network during 3 years, in order to establish the performance category of the system.

2. CASE STUDY AND RESULTS

The water distribution network submitted to this study covers the water consumer demands from a Romanian district places in the north-west of the country. The layout of the distribution network is a mixed one with a 21.87 km length and with cement asbestos, cast iron, polyethylene and steel pipes. The specific length of this type of pipes are $L_{cement\ asbestos}$=7066.2 m, L_{steel}=2672.4 m, $L_{cast\ iron}$ =2880.6 m and $L_{polyethylene}$= 9254.2 m with diameters range from 63 mm up to 400 mm.

The number of the connections do not exceed 1000, so the District Metered Area (DMA) is situated in the lower range of the optimum size of 500 up to 3000 (IWA, 2007; Sardinha J., 2017).

The data analysed in this study were gathered during 3 years: 2017, 2019 and 2020. Because of technical problems some data measured in 2018 were lost therefore the 2018 years is not included in the study.

Based on the in situ measurements and IWA recommendation (IWA, 2000) the following steps were covered in order to assess the performance category of the network:

2.1 *NRW* as percentage value

The relation used in the determination of the *NRW* is (IWA, 2000):

$$\%\ NRW = \frac{\text{Volume of Lost Water}}{\text{System Input Volume}} \cdot 100 \qquad (2)$$

The annual water balance is used to assess the water losses and to calculate the % *NRW* for the following years: 2017, 2019 and 2020 (see figure 2). The results obtained for %*NRW* are presented in the table 2.

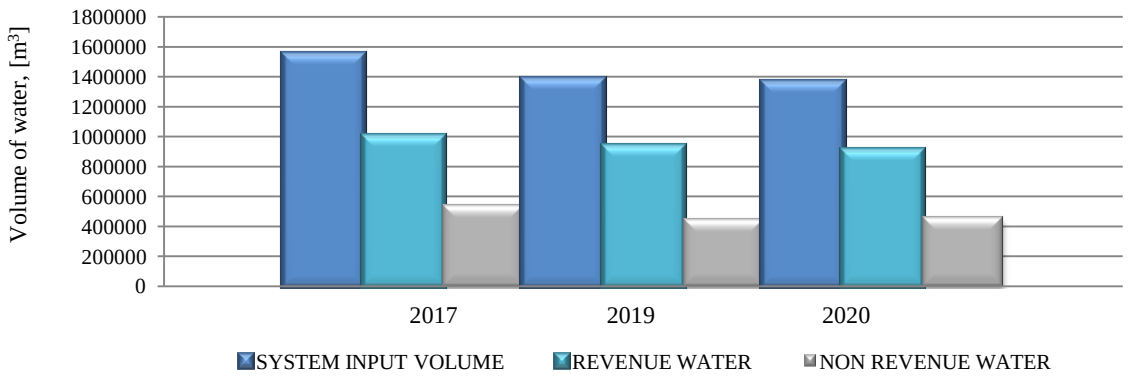


Figure 2. Annual water balance for 2017, 2019 and 2020

Year	*NRW* %		*LKN* (m³/yr./conn.)		*ILI*		*ELI*	
	Value	Category	Value	Category	Value	Category	Value	Category
2017	35.18	C4	24270.62	C3	24.98	C3	3.37	C4
2019	32.61	C4	18986.00	C2	19.53	C2	2.64	C2
2020	33.61	C4	20425.42	C3	20.98	C3	2.84	C2

Table 2. Performance indicators values

As expected, the analysis of the obtained results of *NRW* values indicates a slight variation during those 3 years. The lowest water losses are detected in 2019 and the highest values in 2017 because of some technical faults that occurred in the network. A detailed variation of the *NRW* values throughout those 3 years is shown in the figure 3. The obtained *NRW* values for each month of the years indicate in fact the real situation of the operating network between each of those 3 years.

By analysing the monthly *NRW* values shown in figure 3 it can be observed a significant variation of the *NRW* values throughout 2017. Thus, at the beginning of the year, between January and April the *NRW* values indicate a gradually growth of the water losses that validated the fact that in the network some faults occurs.

In May and June after some technical repairs made in the water network, the water losses were reduced.

The *NRW* value for July points out the presence of other faults in the network, faults that were adjusted.

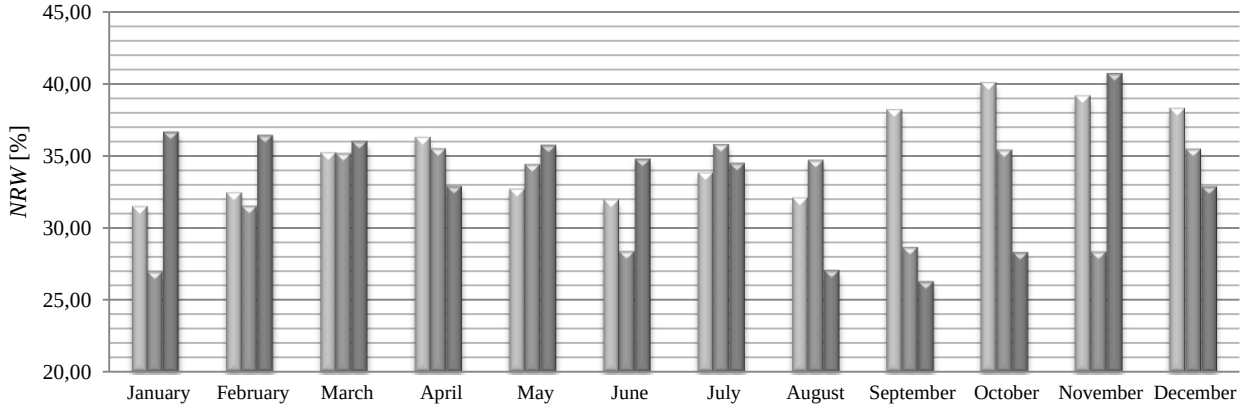


Figure 3. Monthly variation of *NRW* for 2017, 2019 and 2020

Then, at the end of the year 2017 unidentified faults existing in the water distribution network, lead to a gradual and continuous growth of the water losses.

For 2019 the *NRW* mean values indicate the adjustment of the 2018 faults. Nevertheless, the water losses increased from September to December confirm the presence of other problems in the network.

By evaluating the *NRW* values for the year 2020, it appears that at the beginning of year the *NRW* values are still high although, during 2018 and 2019 the faults were restored. The highest value of the *NRW* out of these 3 years was reached in November 2020, as a result of new fault within the network.

2.2 Infrastructure Leakage Index *(ILI)*

ILI performance indicator (Lambert A., 1999) as the ratio of the current annual real losses and the theoretic minimum level of the losses also known as unavoidable annual real losses is given by the relation:

$$ILI = \frac{CARL}{UARL} \tag{3}$$

where: *UARL* is Unavoidable Annual Real Losses
CARL - Current Annual Real Losses (expressed in same units as *UARL*) (Lenzi C. and Fortini M., 2014). It can be calculated with one of the following relations:

$$CARL = \frac{\text{Real losses} \cdot 1000}{T_p} \text{ (litres/day)} \tag{4}$$

or,

$$CARL = \frac{\text{Real losses} \cdot 1000}{T_p \cdot N_c} \text{ (litres/day/service connection)} \tag{5}$$

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

As mentioned before, the *NRW* indicator depends on the water losses and to be more specific on the apparent and real losses.
A good estimation of the apparent losses represents a very important aspect (Vermersch M. et al., 2016) because of its impact on the real water losses that influences the *ILI* values (Seago C. et al., 2005).

The components of the apparent losses are: meter under-registration, meter reading errors, water accounting errors and water theft (Rizzo A. et al., 2007). Over the years, it was demonstrated that none of these components had a major influence on the highest values for *NRW* due to the fact that the real losses are superior to the apparent losses.

The real losses can be estimated with accuracy if ongoing fault monitoring of a system is employed and therefore the water volumes can be easily calculated (Vicente D. J. et al., 2019). Thus, an accurate monitoring of *NRW* indicator permits to keep its values between optimal ranges via detection, identification and repairs of the faults that can occur into the network.

Another method used to estimate the water real loss is based on the Minimum Night Flow (*MNF*) (Vicente D. J. et al., 2019). Thus, throughout the night hours, to be more exactly between 2 and 4 a.m., the correspondent time of *MNF*, the minimum consumption is reached so the pressure cans growth uncontrollable and therefore the probability of a failure arise. This is not the case for a daily hourly consumption when the pressure is much lower (AL-Washali T. et al., 2019; Özdemira Ö. et al., 2021).

For the water distribution network under study the *MNF* values were gathered during those three years and the values are presented in the figure 4. It seems that the night pattern of the consumers for the years 2019 and 2020 was quite similar, instead for 2017 the night consumption was superior, probably due to the changes in the human behaviour in ratio with the prices of the water.

Once the *MNF* values are known, the real losses during a day can be calculated with the relation:

$$RL_t = RL_{MNF} \cdot \left(\frac{P_t}{P_{MNF}}\right)^{N_1} \quad (6)$$

where: RL_{MNF} is real losses during minimum night flow. It can be determined with the following relation:

$$RL_{MNF} = MNF - C_{MNF} - AP_{MNF} \quad (7)$$

MNF - water volume that corresponds to the minimum night flow (between 2 and 4 a.m.);
C_{MNF} - consumed volume during *MNF*;
AP_{MNF} - apparent losses during *MNF*;
P_t - hourly average pressure;
P_{MNF} - pressure during MNF;
N_1 - leakage exponent with values between 0.5 and 2.5, (Tabesh M. et al., 2009). These values depend on the pipe type: rigid or flexible (Greyvenstein B. and van Zyl J. E., 2007) and on the network characteristics. In case of a large network with a mix of pipe materials the value of N_1 becomes 1.0 (Farley M. et al., 2008).

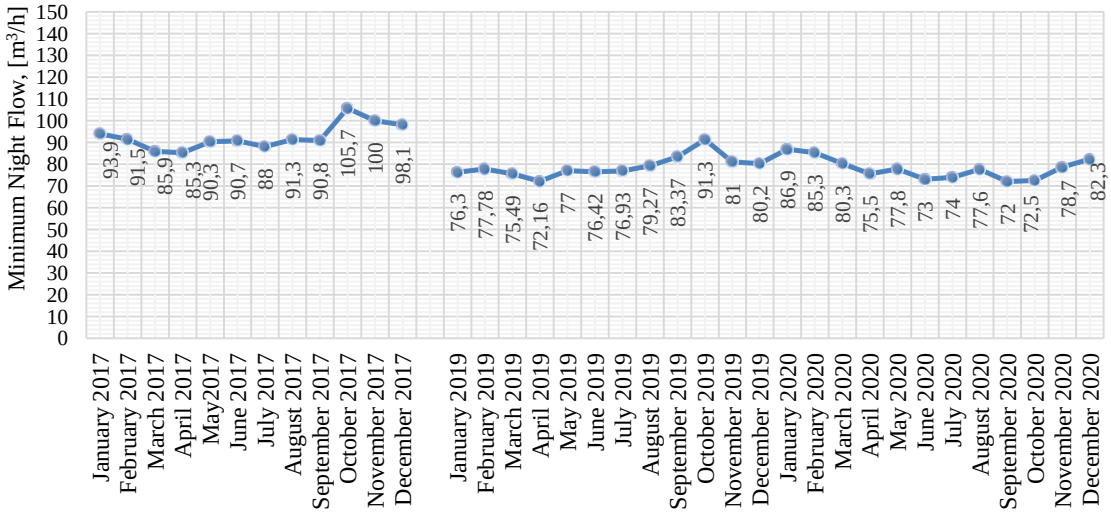


Figure 4. *MNF* values for the years 2017, 2019 and 2020

A more simplified relation to calculate the real losses based on *MNF* founded in the technical literature (Araujo L.S. et al., 2003) is:

$$RL_{MNF} = 0.8 \cdot MNF \quad (8)$$

This relation along with the measured data for 2017, 2019 and 2020 were used in order to calculate the real losses. The results are shown in the figure 5. By comparing the pattern of the curves from the figures 4 and 5 it results that this pattern is the same, aspect that confirms the major influence of the *MNF* on the real losses.

For the calculation of *UARL* the technical literature (Peiris L.L.A et al, 2008, Lambert A. and McKenzie R, 2002) proposes the following relation:

$$UARL = (18 \cdot L_m + 0.8 \cdot N_c + 25 \cdot L_p) \cdot P \text{ (Litres/day)} \quad (9)$$

where: L_m is main length in km (without service pipes);
N_c - number of service connections;
L_p - the total length of service connections in km;
P - average operating pressure in meter.

As it can be seen in relation (9), besides the density of connections and length of connections also the average operating pressure of the system has a great influence on *UARL* value (Winarni W., 2009), therefore an accurate method to evaluate the average pressure becomes necessary.

In this study, in order to calculate *UARL* geometric characteristics of the network and measurements made in some sections of the network related to the centre of gravity, were used.

Once the values of *CARL* and *UARL* are known the *ILI* indicator can be calculated by using equation (3). The values obtained for *ILI* indicator are presented in table 2. It can be seen that for the years 2017 and 2020 the values of *ILI* are over 20, so the performance category of the studied water network was C3 and for the year 2019 the performance category, C2.

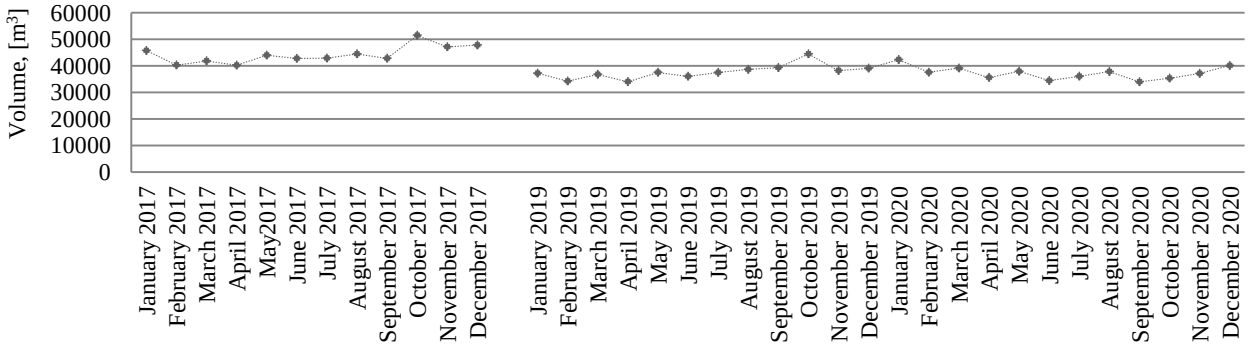


Figure 5. Real losses during the years: 2017, 2019 and 2020

2.3 Leakage on the Network Kilometre (*LKN*)

In order to maintain a low level of *NRW*, it is important to take into consideration technical status of the network expressed in losses by km of network length, too. It can be expressed with the relation:

$$LKN = Q_{RL}/L_m \text{ (m}^3\text{/year/km)} \quad (10)$$

where: Q_{RL} represents real losses.

The values obtained for this indicator are presented in table 2.
The analysis of the obtained *LKN* values for the years 2017 and 2020, show that these values are over 20000.00 m^3/yr./conn., so the performance category of the studied water distribution network was C3. Since the total length of the water network was identical for each year, it results that the real losses for the year 2019, values that indicates a C2 performance category, were slightly reduced.

2.4 Economic Leakage Index (*ELI*)

It is necessary that the water operators should evaluate the economic value of the acceptable water losses. The value of the *ELI* index implies the Economic Index (*EI*) and Leakage Index (*LI*) and is given by the relation:

$$ELI = EI \cdot LI \quad (11)$$

The recommended values for the indices are:
EI = 1,5 - the water within the system is twice treated and then is pumped into the network at min. 5 bar pressure
EI = 1,0 - the water within the system is twice treated and then is gravitational driven into the network or the water needs to be only disinfected but is then pumped into the system
EI = 0,5 - the water needs to be only disinfected and then is gravitational driven into the network
In the case of *LI* the following relation it can be applied:

$$LI = LKN/3600 \quad (12)$$

By using the above relations from 1 to 12 and based on measurements in situ, the performance indicators values were assessed for the considering network during the years: 2017, 2019 and 2020. The results are synthesized on the table 2.

Once, the Performance Indicators are known, the next step in this study was to establish the performance category of the operational water distribution system, based on the methodology presented above.

The results are:
- for 2017: it results C4 category if the *NRW* and *ELI* values are used and C3 category if *LKN* and *ILI* values are used;
- for 2019: it results C4 category if the *NRW* value is used and C2 category if *LKN*, *ELI* and *ILI* values are used;
- for 2020: it results C4 category if the *NRW* is used, C3 category with *LKN* and *ILI* values and C2 category if *ELI* value is used.

By analysing these results, it became very difficult to decide in which category of performance the studied water distribution network can be placed and moreover, which performance indicator reflects the real performance of the network.

3. CONCLUSIONS AND RECOMMENDATIONS

Broadly, *NRW* is the only indicator used in the procedure of establishing the performance category of a system. In this case, the *NRW* is calculated by dividing the total volume of lost water to the total system input, wherefrom the reason why the *NRW* is the most widely used performance indicator. Nevertheless, *NRW* has several shortcomings such as: the real losses on the kilometre network, ratio between physical and commercial losses and hydraulic characteristics of the flow: supply time and average operating pressure, aspects that are not taken into consideration by the *NRW*. These aspects are included in other performance indicator to be more precisely *ELI* and *LKN* and therefore *ILI*, too.

Therefore, for the distribution network presented in this study, which it can be integrated into the small network type, the results obtained indicate that the performance indicator that gives the real performance of the system is *ILI*. Hence, the work done within this paper is in agreement with the studies focused on the networks with DMAs for maximum 1000 consumers, founded in the technical literature. Therefore, to reduce the water losses from a small distribution network the actions given by the C3 performance category, meaning the identification of a possible faults, must be applied.

It is important to mention that the implementation of the water loss reduction programs are required for any water distribution system that has a *NRW* value greater than 10%. The future proposed actions must be based on the state of the water distribution network or on the analysis of the current *NRW*. These actions must be gradually implemented in order to reduce the water losses.

In terms of rehabilitation, the replacement or the expansion of the system is recommended to setup a strong programme that will include besides a *NRW* master plan, also an adequate selection of the pipe material (Maiolo M. et al., 2018) based on the priorities of the investors and in accordance with the sustainable development principles.

Nevertheless, the least expensive method that can be used to reduce the water losses within a distribution network is pressure control. By lowering and maintaining the pressure at a minimum value that correspond to a normal functioning of the system, the network pipes can be protected at reiterative loads. Thus, a proper water pressure management becomes mandatory.

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