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Indirect condition assessment of water mains

L. Tuhovčák[a]*, M. Tauš[a], P. Míka[a]

[a]*Institute of Municipal Water Management, Brno University of Technology, Veveří 95, Brno 602 00, Czech Republic*

Abstract

The knowledge of the technical condition of the water distribution systems (WDS) is a key issue to predict the performance of the WDS and to optimize maintenance and rehabilitation of the WDS. Common practice employs only practitioner experience to assess the technical condition of the WDS. The presented paper summarizes a basic theory of indirect condition assessment including several definitions of condition assessment, factors contributing to deterioration and possible outputs of the condition assessment. Furthermore, the legal requirements concerning this issue specifically in the Czech Republic and the Slovak Republic are listed. There is also a summary of the studies of condition assessment methods of water mains.
As a part of the intended complex methodology for condition assessment of WDS, a methodology for condition assessment of water mains was developed. The methodology is based on condition indicators (CI) formulated using a multi-objective optimization. The paper presents the proposed methodology and its application in two case studies. The proposed methodology achieved good results and it showed certain significant benefits – e.g. satisfactory level of detail, optional user modification.

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Keywords: Water distribution system; water mains; deterioration; condition assessment; condition rating

1. Introduction

The aging water infrastructure is a worldwide issue. For example, it is estimated that a total of US 77 billion will have to be invested in the water supply system reconstruction in the USA over the next 20 years (Al-Barqawi and Zayed, 2006b). Al-Barqawi and Zayed (2008) states that a total of 59 % of Canadian water distribution systems call for rehabilitation and 43 % of these systems are in a technically poor condition. Estimates made in the Czech

* Corresponding author. Tel.: +420-541-147-720; fax: +420-541-147-728.
E-mail address: tuhovcak.l@fce.vutbr.cz

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Republic show that the water distribution system rehabilitation requires approximately USD 1 billion a year; but in reality, the annual investments are well below 0.35 billion (Barák, 2012).

The basic precondition for a sustainable condition of the water infrastructure is a continuous planned reconstruction of the infrastructure. The best possible knowledge of the technical condition of the WDS should be in the interest of every owner or operator of the water mains. Such knowledge should form the background for investment projects decision-making and, in particular, water mains rehabilitation planning. Knowing the condition of the water mains is also fundamental for predicting the performance of the water mains and for the maintenance and rehabilitation optimization. In normal practice, there is no standardized methodology designed to make the condition assessment (CA) of the water mains (Al-Barqawi and Zayed, 2006a). Therefore, empirical knowledge of the operators‘ staff takes precedence. The effective assessment of the condition requires the involvement of specialist staff, reliable operation databases and a permanent continuous monitoring and assessing of the condition of the operated infrastructure. It is advisable to first conduct a quick assessment of the condition and then take a decision on whether it is necessary to make a more detailed assessment (Rahman and Zayed, 2009).

1.1. Definition of condition assessment

The following chapters provide a brief overview of the theoretical basis of indirect condition assessment of water transmission mains. The condition assessment can be defined as „*a process of measuring the physical condition of the system elements using objective and subjective criteria. The process should consider safety and structural integrity, capacity, quality of services, role within the system, age etc.*" (Rahman and Zayed, 2009). According to another definition, the assessment is „*collecting data and information by means of direct and/or indirect methods followed by the data and information analysis to determine the current and/or future structural and hydraulic condition and water quality*" (U.S.EPA, 2007).

Although the indirect methods are not able to provide the necessary level of detail, timeliness and reliability necessary to make decisions on the repair and rehabilitation of parts of the systems with strong burst implications (U.S.EPA, 2007), they can still provide valuable information. It is advisable to first conduct a quick assessment of the condition and then take a decision on whether it is necessary to make a more detailed assessment (Rahman and Zayed, 2009). The indirect assessment uses the following data (U.S.EPA, 2007):

- historical data (e.g. pipe age, manufacturer, experience with various types of pipe material);
- environmental data (e.g., soil condition, level of groundwater, surface load tec.);
- operating data (e.g. flow rate, repair and maintenance records).

1.2. Factors affecting the technical condition of water transmission mains

The burst rate and deterioration of water mains are affected by a number of factors. These factors include operating, environmental and physical characteristics (Rajani and Kleiner, 2001). Kleiner and Rajani (2002) divide factors causing the water main deterioration into:

- static factors – invariable over time (e.g. pipe material, pipe diameter, pipe wall thickness, soil properties, laying method);
- dynamic factors – these are related to the environment affecting the pipe (e.g. age, soil properties, soil and water temperature, humidity, electric resistance, dynamic load);
- operating factors – i.e. the rate of renewal, cathodic protection, water pressure.

BEST PRACTICES (2003) classify factors contributing to the deterioration into similar groups:

- physical factors – pipe material, wall thickness, year of installation, profile, type of joints, tensile load, external and internal pipe protection, contact between various types of metal, year of pipe manufacture and production process;

- environmental factors – soil type, soil moisture, presence of groundwater, climate, pipe location in a carriageway, backfill material, pipe bed, underground faults, stray currents, seismic activity, pipe laying method;
- operating factors – water pressure, water leakage, water quality, flow velocity, operation and maintenance.

1.3. Condition assessment output information

The output of the condition assessment can have various forms. It may have a form of engineering calculations, determination of the burst probability, remaining service life, marking (categorisation) of the condition (Marlow et al., 2007). As stated by Marlow et al. (2007), the determination of the burst probability or the remaining service life may be difficult and hardly comparable. It is often more achievable to determine the threshold values of the condition and performance when a certain intervention has to be ensured and to make an assessment of whether the relevant system element has reached the threshold values.

One of the examples is the scale for numerical and verbal condition assessment of water mains designed by Al-Barqawi and Zayed (2006a, b). The scale is related to the relevant recommended intervention. Figure 1 shows the graphic representation of the proposed scale. The marking (categorisation) assessment provides useful overall information but entails a major loss of information (Marlow et al., 2007).

Fig. 1. Graphic representation of the condition scale according to Al-Barqawi and Zayed, source: Al-Barqawi and Zayed, 2006a.

1.4. Legislative requirements in the Czech Republic and Slovakia

The law of the Czech Republic imposes a duty to develop and implement water mains and sewers rehabilitation financial plans; however, this is only a plan defining funds to be allocated for the rehabilitation and which are determined as a percentage of the deterioration of assets. The law does not stipulate the method of determining the deterioration rate and leaves it up to the owner of the water mains to determine it. Furthermore, under Act (Czech Republic, 2001), the Ministry of Agriculture may order a technical audit. Under the law, the technical audit of water mains and sewers is defined as: „a specialised expert operation to check the technical condition of water mains and sewers, eligibility of opex as well as capex incurred and costs of the proposed development of water mains and sewers"(Czech Republic, 2001).

In the Slovak Republic, the law (Slovak Republic, 2002) imposed a duty on the owner of public mains to develop the water main rehabilitation plan covering a minimum of 10 years. The basic condition for including the water infrastructure structures and equipment in the rehabilitation plan is the condition assessment following these indicators:

- age;
- burst rate;
- capacity use;
- compliance with the applicable law.

The assessment is conducted by classifying the civil structures and equipment in each of the specified indicators into one of 4 categories. These categories are assigned points from 1 (the best) to 4 (the worst). The relevant structure is included into the relevant category based on the product of points given to all indicators.

The condition assessment of water mains is required by law in other countries, too. For example, water utilities in Scotland are obliged to report the condition of their assets in a form showing what percentage falls within the specific category of the condition assessment. The situation is similar in England and Wales where such a report is required every 5 years. However, none of these countries define any uniform methodology of conducting the condition assessment (Marlow et al., 2007).

1.5. Existing CA studies of water mains

In response to the amended Act on Water Supply and Sewerage Systems (Czech Republic, 2001) introducing the duty to develop the reconstruction financial plans from 2008 onwards, there has been an effort in the CR to develop various multi-objective methods for the condition assessment of water mains. Where the results of such unique attempts have been applied, it only has a form of internal methodologies of the utilities developing them.

Al-Barqawi and Zayed developed a condition assessment model for water mains based on the AHP method (Al-Barqawi and Zayed, 2006a) and a model of artificial neuron networks ANN (Al-Barqawi and Zayed, 2006b) in later joined these methods and introduced a condition assessment method using the AHP and ANN methods (Al-Barqawi and Zayed, 2008). These methods employ the proposed assessment scale including the relevant recommended steps, see Figure 1 above. The assessment criteria were designed for this model including physical, environmental and operating indicators. The proposed indicators were the following: type of soil; type of traffic/road; type of supply system; groundwater level; pipe diameter; pipe material; pipe age; burst rate; coefficient C; cathodic protection, operating pressure.

Another application of neuron networks for the condition assessment of the water mains was tested by Zong et al. (2011). The assessment indicators were as follows: pipe material; pipe diameter; operating pressure; internal pipe protection; external pipe protection; cathodic protection; pipe laying method; type of soil; pipe age; depth of installation; number of road lanes over the water main. The model was tested in water mains in South Korea.

It may be said that the proposed condition indicators correspond to the inferential indicators. U.S. EPA (2012) defines a number of inferential indicators for water mains proving a potential presence of processes causing pipe deterioration, but without the knowledge of whether these processes really occur. The indicators are specified for the individual pipe materials, the following indicators repeat most often:

- pipe material, year of manufacture and origin of pipes, production and installation procedures;
- type of pipe joints;
- water quality;
- water pressure (operating pressure, magnitude and frequency of pressure fluctuation);
- surface load;
- groundwater level;
- type of soil/roundfill or backfill;
- cathodic protection;
- stray currents;
- etc.

2. Proposed methodology

The proposed methodology of the condition assessment of water mains employs the FMEA method. The FMEA method (Failure Mode and Effects Analysis) is a method for analysing reliability which makes it possible to determine the failures with major consequences affecting the function of the system and its elements. The condition assessment procedure for water mains based on the proposed methodology is as follows:

- Selection of a main to be assessed;
- The assessed main must be divided into sections in a suitable manner based on the age, pipe material, etc.
- Collection of information and data to determine or calculate the indicator values;

- Categorisation of the specific sections of the water mains based on the values of the technical indicators according to the defined categories;
- Calculation of the general category of the technical condition of specific sections;
- Calculation of the general category of the technical condition of the entire main;
- Proposed potential measures, inclusion in the rehabilitation plan;
- Setting of the next assessment period.

To evaluate the water mains using the FMEA method it is necessary to identify Technical Indicators (TI) (Tuhovčák et al., 2007). For each specific indicator it is necessary to define the method of its determination, input data, physical dimension and presentation. Based on practical experience and professional knowledge, the following indicators in Table 1 were designed for a quick and effective condition assessment of the water mains.

Table 1. The proposed technical indicators

TI 1 – Age and type of pipe material of the water mains
The commonly used pipe materials show various service life durations. In this indicator, each section is classified into a specific category based on the age, pipe material, external and internal protection.
TI 2 – Hydraulic capacity
This indicator makes it possible to assess whether the relevant main complies with the maximum flow rates given the optimal use of the pipe dimension. The pipe undersizing/oversizing is assessed based on the hydraulic model.
TI 3 – Impacts on water quality
The quality of conveyed water is also affected by the pipe material and, conversely, the pipe service life is influenced by the quality of conveyed water. This indicator reflects the type of the source of raw water, quality of water at the beginning of the main, pipe material and internal surface, retention time and sanitary treatment of water.
TI 4 – Water hammer protection
This indicator assesses the protection of the main against undesirable effects of water hammer. This indicator reflects the method and age of the water main shock protection, physical and hydraulic parameters of the main affecting the occurrence and magnitude of the water shock.
TI 5 – Water main burst rate
The burst rate is one of the basic indicators of the water mains condition. To conduct this basic condition assessment of the mains, the „burst rate“, defining the number of bursts per km and year is calculated, with the exception of valve bursts.
TI 6 – Water losses
To assess water losses in the main, two sub-indicators are proposed. *TI 6.1 Apparent water losses during bursts indicator* (ALI) is expressed as a proportion of the total volume of water leaking during apparent bursts to the total volume of water supplied to the relevant part of the assessed main. *TI 6.2 Unit leakage indicator* (ULI) is expressed as a proportion of the total volume of water leaking during the water transport through the relevant main (apparent and hidden leakage) to the total length of the assessed main section. The summarised TI 6 assessment is calculated as a weighted sum of both these sub-indicators. The sum of weights must equal 1. The recommended weight values are $w_{6.1}$=0.3 and $w_{6.2}$=0.7.

Based on the values of the technical indicators, the assessed water main sections are classified into specific categories. The individual elements are assessed based on the certain TI using the indicator thresholds defined in a table. A table with the specific category thresholds is defined for every single indicator. The following categories were defined end (Tuhovčák et al., 2007):

- C1 (excellent) – optimal condition of the relevant indicator, no measures to change the indicator values are required;
- C2 (good) – low risk rate of the relevant TI and no principal measures are required;
- C3 (average) – these are average values of the relevant TI not requiring an immediate solution;
- C4 (critical) – critical values of the specific indicator. Measures should be planned or taken to address the condition;
- C5 (state of disrepair) – undesired condition requiring an immediate solution.

The total category of the condition of each water main specific section (TCS) is then determined as a weighted sum of the categories of all indicators based on the following formula:

$$TCS = \sum_{i=1}^{n} TI_i * w_i \tag{1}$$

where

n the number of used technical indicators,

TI_i the value of the indicator category,

w_i the indicator weight.

The indicator weights can be determined ad-hoc as required by the assessor while keeping the condition $\sum w_i=1$.
The total technical condition of the evaluated water main (TCM) is then calculated as a weighted sum of the TCS of the specific sections with the weight being the length of the section based on the following formula:

$$TCM = \frac{\sum_{j=1}^{m} TCS_j * L_j}{L} \tag{2}$$

where

m the number of sections,

TCS_j the category of the condition of the specific section,

L_j the length of the section,

L the total length of the water main.

The assessed water main is then included based on the TCM into the relevant condition category according to Table 2.

Table 2. Category of the condition of the water main

Category	Description	TCM [-]	Wear Rate [%]
C1	Satisfactory condition, requiring no action	1.00-1.25	< 10
C2	Satisfactory condition, actions under normal operation, it is not necessary to include in a rehabilitation plan	1.26-2.00	10-30
C3	Conditionally satisfactory condition, a need to tackle individual problems, prospective need of rehabilitation	2.01-2.50	30-50
C4	Limit values of partial indicators, relevant actions needed, include in a rehabilitation plan	2.51-3.75	50-80
C5	Critical condition of assets, acute risk, threatened functionality, immediate rehabilitation needed	3.76-5.00	>80

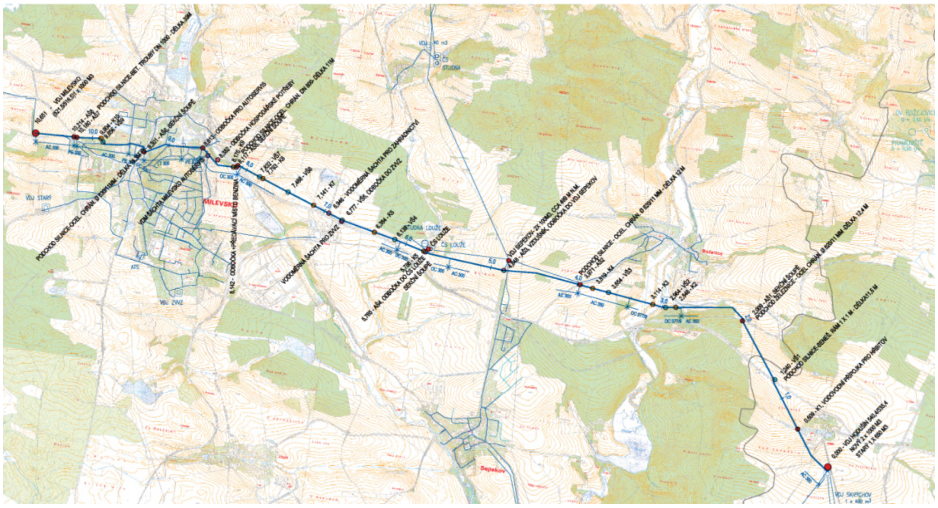

Fig. 2. Layout of the VDJ Hodušín– VDJ Milevsko water main (Míka, 2012) [9]

Table 3. Assessment of the condition of the VDJ Hodušín-VDJ Milevsko water main (Míka, 2012)

Conduit: VDJ Hodušín - VDJ Milevsko
Date : **april 2012**
Evaluator : **Míka Petr**

Parameters of sections					Categories by TI's						Total	
Section no.	DN	Material	Length	Age	TI 1	TI 2	TI 3	TI 4	TI 5	TI 6	TCS	TCM
[-]	[mm]	[-]	[m]	[years]	w_1 0.09	w_2 0.20	w_3 0.15	w_4 0.05	w_5 0.24	w_6 0.27	[-]	[-]
1	350	AC	609	43	C4	C1	C3	C2	C1	C1	1.62	**C2** , Wear rate 10-30%
2	350	AC	2 177	43	C4	C1	C3	C3	C1	C1	1.67	
3	350	S	594	43	C3	C1	C5	C3	C4	C1	2.60	
4	350	AC	591	43	C4	C1	C3	C3	C1	C1	1.67	
5	300	AC	877	43	C4	C1	C3	C2	C1	C1	1.62	
6	300	AC	612	43	C4	C1	C3	C2	C1	C1	1.62	
7	300	S	305	43	C3	C1	C5	C2	C1	C1	1.83	
8	300	S	315	43	C3	C1	C5	C2	C1	C1	1.83	
9	300	AC	697	43	C4	C1	C3	C2	C1	C1	1.62	
10	300	AC	169	43	C4	C1	C3	C2	C1	C1	1.62	
11	300	AC	1 124	43	C4	C1	C3	C3	C1	C1	1.67	
12	300	S	72	1	C1	C1	C3	C3	C1	C1	1.40	
13	300	S	240	1	C1	C1	C3	C3	C1	C1	1.40	
14	300	S	202	1	C1	C1	C3	C3	C1	C1	1.40	
15	315	PE	35	2	C1	C1	C2	C3	C1	C1	1.25	
16	315	PE	248	2	C1	C2	C2	C3	C1	C1	1.45	
17	300	CI	434	43	C2	C2	C5	C2	C4	C1	2.66	
18	315	PE	230	16	C1	C2	C2	C2	C1	C1	1.40	
19	300	AC	649	43	C4	C2	C3	C2	C1	C1	1.82	
20	315	PE	34	16	C1	C2	C2	C3	C1	C1	1.45	
21	300	AC	437	43	C4	C2	C3	C3	C1	C1	1.87	

AC - Asbestos Cement, CI - Grey Cast Iron, PE - Polyethylene, S - Steel
TCS - Technical Condition of Section, TCM - Technical Condition of Main

3. Case studies

The proposed methodology was tested by Míka (2012) on water transmission mains of the Southern Bohemia Water Supply System (hereunder the „SBWS“) owned and operated by Jihočeský vodárenský svaz (hereunder the „JVS“). The SBWS has a total length of 540 km and supplies water to approx. 380,000 inhabitants of the South Bohemian Region. Two water mains were selected for testing the proposed methodology (VDJ - water reservoir):

- VDJ Hodušín-VDJ Milevsko
- VDJ Hodušín-VDJ Všechov

The assessed mains were divided into sections based on, for example, pipe material, profile and age and the specific sections were assessed using the presented methodology by means of the proposed technical indicators TI1 – TI6.

3.1. VDJ Hodušín-VDJ Milevsko

This water transmission main is 10,651m long and was constructed in 1969. Various pipe materials were used for the construction (grey cast iron, steel, asbestos-cement) with various nominal profiles. Some sections of the water main have been reconstructed. The layout of the main is presented in Figure 2.

Table 3 indicates the influence of the specific sections and indicators of the condition assessment. The pipe material of a major part of the water main is approaching the end of its service life and therefore these sections were included in the TI1 indicator under category C4. Other indicators show that the condition of the individual sections differs to a large degree and therefore, the water main cannot be assessed as a whole. The condition indicator of the TCS section according to the proposed methodology detected two critical sections of the conduit and, in general, the conduit was classified under the C2 category of the general condition of the TCM conduit.

3.2. VDJ Hodušín-VDJ Všechov

This water transmission main, 11,222 m long, was constructed in 1969. The water main is made of steel and cast iron pipes of various profiles. This water main has not been reconstructed yet. The layout of the water main is shown in Figure 3.

With regard to the second assessed main, the usefulness of assessing the main in section was proved, too. The proposed methodology again revealed a critical section with a high burst rate and given the other indicators it was included under the C4 category.

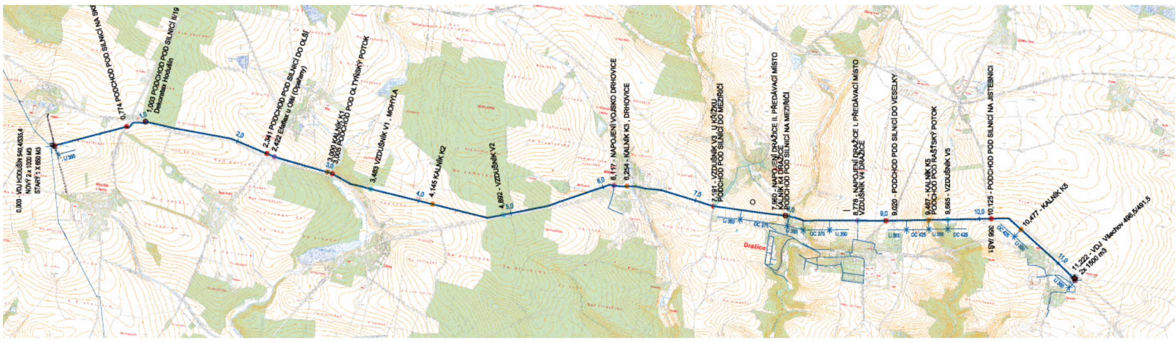

Fig. 3. Layout of the VDJ Hodušín– VDJ Všechov conduit (Míka, 2012)

Table 4. Assessment of the condition of the VDJ Hodušín-VDJ Milevsko conduit (Míka, 2012)

Conduit: **VDJ Hodušín - VDJ Všechov**
Date : **april 2012**
Evaluator : **Míka Petr**

Parameters of sections					Categories by TI's						Total	
Section no.	**DN**	**Material**	**Length**	**Age**	**TI 1**	**TI 2**	**TI 3**	**TI 4**	**TI 5**	**TI 6**	**TCS**	**TCM**
[-]	[mm]	[-]	[m]	[years]	w_1 0.09	w_2 0.20	w_3 0.15	w_4 0.05	w_5 0.24	w_6 0.27	[-]	[-]
1	350	CI	1 000	43	C2	C3	C5	C1	C1	C1	2.09	**C3**, Wear rate 30-50 %
2	350	CI	422	43	C2	C3	C5	C2	C1	C1	2.14	
3	350	CI	4 695	43	C2	C3	C5	C2	C1	C1	2.14	
4	350	CI	1 383	43	C2	C3	C5	C2	C1	C1	2.14	
5	375	S	460	43	C3	C3	C5	C2	C1	C1	2.23	
6	350	CI	250	43	C2	C3	C5	C2	C1	C1	2.14	
7	375	S	280	43	C3	C3	C5	C2	C1	C1	2.23	
8	350	CI	288	43	C2	C3	C5	C1	C1	C1	2.09	
9	350	CI	458	43	C2	C3	C5	C2	C1	C1	2.14	
10	425	S	260	43	C3	C3	C5	C2	C1	C1	2.23	
11	350	CI	200	43	C2	C3	C5	C2	C1	C1	2.14	
12	425	S	751	43	C3	C3	C5	C2	C3	C1	2.71	
13	350	CI	775	43	C2	C3	C5	C2	C1	C1	2.14	

CI - Grey Cast Iron, S - Steel
TCS - Technical Condition of Section, TCM - Technical Condition of Main

4. Conclusion

Although there are legislative duties to regularly report the condition of the water infrastructure, there is no methodology in place in most of the cases to be followed in assessing the condition. The presented study of the condition assessment of water mains provides good results but these may be too much complicated for the water management situation in the Czech Republic. Besides large water utilities, there are a number of small water utilities in the market where a lack of funds and qualified staff to conduct the condition assessment may be assumed. Therefore, the effort is to present a simple condition assessment methodology.

The proposed methodology may detect critical sections of the operated main; nevertheless, the entire assessment table must be made available rather than the final water main assessment. Experienced operators may adjust the assessment process based on the methodology. The category thresholds for the specific indicators can be selected along with the definition of preferences of the indicators through weighted indices.

Work has currently started on drafting a uniform comprehensive methodology for the condition assessment for the most important water system elements – water intake structures, water treatment plants, pumping stations, water reservoirs and distribution network.

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