Technical auditing of water supply systems – part 2: water treatment plant

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ABSTRACT

This paper presents a comprehensive method for assessing the technical condition of water treatment plants as part of a set of procedures for assessing the entire water supply system. The proposed method of water treatment plant assessment is based on a system of technical indicators and factors. Based on these, the assessment of the technical condition is carried out as a two-stage process, where the evaluator first determines discrete values of the factors. The point score given to these factors is then aggregated and used to calculate the values of individual indicators, indicating the overall condition of the water treatment plant. The proposed set of assessment indicators therefore includes two types of indicators: structural–technical and technological–operational. The paper includes a case study demonstrating the use of the proposed technology to assess the technical condition of an actual water treatment plant. This methodology makes it possible to highlight critical parts of the system and, as the case may be, prioritise the elements in terms of their technical condition, which can then be used in the repair and reconstruction planning process.

Key words | evaluation, technical condition, water supply, water treatment plant

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INTRODUCTION

The basic mission of water utilities is to supply safe drinking water that meets the quality requirements laid down by legislation. The most important principle when managing and planning the operation of a drinking water distribution system is to satisfy consumer requirements.

A reliable distribution system is expected to deliver water of the required quality and pressure at any time for all consumers. A considered bonus occurs if a water supply enjoys consumer trust (International Water Association 2004). However, besides this prime objective, water utilities also focus on how to operate the entire water supply system in a cost-effective and sustainable manner. They endeavour to focus on the design and construction of new facilities within the water supply system in order to achieve better efficiency and effective function of the existing systems.

In addition, the current condition of individual components of the system and their behaviour need to be constantly assessed. Only detailed knowledge of the present condition of the system makes it possible to organise a meaningful investment or refurbishment plan.

The attempts to assess these systems have resulted in the development of assessment systems based on a system of performance indicators (PI). The leading and most widespread PI systems are those developed with the support of the International Water Association (Alegre *et al.* 2016) and World Bank (Danilenko *et al.* 2014). The following projects are also worth mentioning: '*Scandinavian Six Cities Group*' (Stahre & Adamson 2002; Stahre *et al.* 2008), AWWA QualServe Program (Crotty 2003), UK Ofwat scheme (Ofwat 2004) and a number of other important studies (Cardoso *et al.* 2004; Vieira *et al.* 2008a, 2008b; Karamouz *et al.* 2008; Kanakoudis *et al.* 2011, 2015).

The available technical condition assessment systems focus more on distribution systems and water mains

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(Al-Barqawi & Zayed 2006; Chhipi-Shrestha *et al.* 2017) and less on the water treatment plants. Not many research studies can be found dedicated to WTP assessment. Some studies were presented on waste water treatment plants (Hernández-Padilla *et al.* 2017). For example, Rahman & Zayed (2009) presented their study focused on the technical condition of selected water treatment plant components. An available methodology assessing the technical condition, which would also reflect the legal requirements concerning water-related facility refurbishment planning, is completely missing in the Czech Republic.

METHODOLOGY

Assessment of the technical condition of water treatment plants is part of the comprehensive methodology of water supply system assessment. All components of the system are considered, including water intake structures, treatment plants, tanks and pumping stations as well as individual water mains. The development of this comprehensive methodology is based on the 'Failure Mode and Effects Analysis' (FMEA) method.

This methodology is divided into seven separate modules. Each module is dedicated to a relevant part of the water supply system (treatment plant, tank, pumping station, conduit, distribution network, etc.). To assess these systems using the FMEA methodology, it is necessary to establish specific *technical indicators* for each module. In contrast to the standard FMEA method, the proposed methodology is improved by another level – factors (F). Technical indicators are not assessed directly, but a set of proposed factors for each individual technical indicator is used for their assessment. Factors are the only level where data is entered into the assessment and assessments at higher levels are calculated using data entered at the factor level.

Therefore, this is a multi-criteria assessment. The proposed comprehensive methodology for assessing technical conditions is based on a weighted sum method. In a weighted sum method it is particularly important to establish weights for the individual factors and indicators. Weights were set in this proposed methodology on the basis of the findings and experience of the research team, as well as on the basis of the results of discussions with water utility staff.

Assessment of the analysed water supply system and its elements is divided into two basic parts in each of these seven modules:

- Structural–technical part (ST) – with structural and technical indicators.
- Technological–operating part (TP) – with technological and operational indicators that have no direct link to the structural and technological condition of the analysed structure.

A more detailed description of the proposed comprehensive methodology, including individual modules, such as TEAN (water distribution networks) and TEAP (pumping stations) modules is described in (Tuhovčák *et al.* 2006, 2016).

APPROACH TO THE ASSESSMENT OF WATER TREATMENT PLANTS –TEAT MODULE

Water treatment plants play an important role in water supply systems both in terms of the quantity and quality of water supplied. While the importance of quantitative aspects prevail in distribution networks, the qualitative aspect of water supply has an increased importance in water treatment plants.

Assessment of the technical condition of water treatment plants is based on the special *TEAT module*, forming part of the comprehensive complex methodology of technical auditing of water supply systems. This module has been developed for both structural–technical aspects as well as operational–technological aspects, while taking into account the quantity and quality of the drinking water produced.

With respect to the water treatment plants, the authors of the comprehensive methodology and its TEAT module fully understand that it is difficult to generalise the entire audit since there are many types of water treatment plants, as well as various technological elements used in them.

The proposed set of assessment indicators is based on the water treatment plant function, i.e. production of drinking water in the required quantity and quality. When assessing technical conditions, they may not be viewed simply in structural and technical terms but it is absolutely necessary and far more important to assess them in technological terms. It is obvious that the resulting product – drinking water – must meet the prescribed indicator values although production process efficiency may differ.

The indicators and factors related to the *Structural–technical part (ST)* of water treatment plants are designed similarly to the water intake structures (TEAR module). The assessment of these indicators focuses on the condition of water tank and wall surfaces (concrete and masonry structures), condition of windows and doors, ventilation and thermal insulation, etc.

Technically speaking, it is recommended that proposed assessment indicators should be used to monitor individual pipelines (e.g. progress of corrosion), functionality of fittings and control elements, as well as the age of pumps and other equipment. Often it is difficult to determine the service life of these components. In general, the described methodology considers a service life limit of 10–15 years for these technologies.

In the *Technological–operating part (TP)* of the assessment, emphasis is primarily placed on the efficiency of drinking water production. The technical conditions are then evaluated both in terms of the water treatment plant as a whole and, specifically, with respect to fundamental process units. These indicators include the treatment plant performance, defined as the ratio between the actual average treatment plant output and the projected output. A favourable ratio is considered to be 90–100%. If the plant capacity is not fully utilised or if the plant is overloaded in hydraulic terms, the efficiency of technological processes is adversely impacted (design flow rate values, surface load and retention time are not followed). An indicator monitoring internal water consumption is used to trend the volumes of water used to operate the process units (flushing water, sludge extraction, rinsing, etc.). A satisfactory situation in terms of internal water consumption is in the range of 3–5% and a value above 10% is considered unsatisfactory (Letterman 1999; AWWA 2000; Rovel 2007; Koleva *et al.* 2016).

In addition to quantitative indicators, qualitative indicators have also been proposed to monitor compliance with the requirements for drinking water quality and the number of exceeded limit values, as well as the standard of the measurement and monitoring equipment at the plant and its degree of automation. With respect to efficiency, it is quite difficult to provide an assessment verdict, and some decisions must be left to each individual assessor. However, the proposed methodology generally recommends the efficiency of removing suspended solids during sedimentation at over 80% to be considered as very good. Similarly, with respect to filtration it is recommended as very good efficiency if the turbidity values in the effluent reach 1.0 NTU (Letterman 1991).

The proposed methodology for assessing technical conditions is conceived in a sufficiently comprehensive manner to accommodate all the key components of water treatment facilities, from all points of view – structural and technical. Besides evaluating individual components, it also provides an assessment of water treatment plants as a whole, which is a major benefit over the existing available assessment methods. The development of the assessment methodology was based on practical applicability and its relationship to the legislative requirements related to the water supply infrastructure renewal planning.

SYSTEM OF PROPOSED INDICATORS OF WATER TREATMENT PLANTS

As indicated above, the system for assessing the technical conditions is based on indicators that are subdivided into factors. As regards water treatment plants, some indicators have been developed that are applicable according to the comprehensive methodology for assessing water supply systems to the Structural–technical part and the Technological–operating part.

Both these aspects must be assessed with equal degrees of attention. However, the authors are of the opinion that the operational and technological aspects require greater attention with respect to water treatment plants. For this reason, it is recommended to assign greater weight in the methodology to this aspect in a ratio of up to 70% to 30% assigned to the Structural–technical parts (Kučera *et al.* 2016).

In the Structural–technical terms, the individual components of civil structures such as buildings are assessed, but technological unit components are also included. The

Structural–technical part in the TEAT module is assessed using three indicators as shown in Table 1.

As regards structural assessment, we present an example of one of the factors related to building walls in Table 2.

As described above in the principles of the methodology, the assessment is made by arriving at a valid (most applicable) verdict at the level of individual factors. The factor is then given a value stated in the given verdict. This applies to structural openings (windows, doors, covers) as well as pipe entries through walls, railings and other elements.

In structural and technical terms, the level of structural protection against ambient conditions is also monitored. Factors included in this indicator are related to how the structure is protected against unauthorised access (e.g. functionality of locks or conditions of window bars). As regards water treatment plants, air contamination and exposure of the water surface to sunlight is also unacceptable – such factors are also listed in the described methodology. Below we provide one of the factors 'Ventilation', as shown in Table 3.

There is considerable experience in the Czech Republic with flooding and, therefore, one of the factors also applies to protecting the water treatment plant against flooding – Q_{100} is taken into account.

Assessment in structural and technical terms forms an integral part of the methodology; however, greater importance is attached here to the operational and technological

Table 1 | Structural–technical part – list of indicators

Indicator	Factors
Condition of civil structures	Ceilings
	Walls
	Floors
	Physical conditions of openings (doors, covers, manholes and windows)
	Stairs, railings, ladders, handles, step boards
	Wiring
	Pipe entries through structures
Condition of technological elements	Concrete tanks
	Metal and other tanks
	Piping systems
	Fittings
	Mechanical fit-outs
Protection of structures against ambient conditions	Doors and windows
	Sunlight
	Ventilation
	Is the water treatment plant located in a Q_{100} floodplain zone?

Table 2 | Structure of the assessment verdicts – walls of a building factor

Indicator	Factor	Score	Description
Condition of civil structure	Walls of a buildings	0	Not assessed;
		1	Intact, no visible defects (cracks, mould, dampness);
		2	Thin cracks, local occurrence of mould and attached organisms, isolated dampness;
		3	Disintegrating surface, distinct cracks, greater areas of mould and attached organisms, visible dampness, water seepage.

Table 3 | Structure of the assessment verdicts – ventilation factor

Indicator	Factor	Score	Description
Protection of a structure against ambient conditions	Ventilation	0	Not assessed;
		1	The structure is ventilated by functional air ducts, ventilation is equipped with an air filter, secured against access by animals and rain;
		2	Some of the air ducts do not work, missing air filter, ventilation is secured against access by animals or the air ducts are not protected against rain;
		3	Ventilation of the structure has limited function, missing air filter or it is not fitted with adequate protection against access by animals or the air ducts are not protected against rain.

part while highlighting the qualitative aspect of water supply. The items shown in Table 4 were included in this category.

As regards the 'Scope of the water treatment technology' indicator, the technological line is also monitored as to whether its composition corresponds to the intensity of raw water pollution. An assessment is made of whether any limit values of drinking water quality, as set down by law, are or have been exceeded or whether it is expected that they could be exceeded in the near future.

One of the important monitored factors is also the frequency of non-complying results of analyses. The structure of statement verdict for the 'Legislation' and 'Frequency factor of the unsatisfactory results of analyses' is presented in Table 5.

Table 4 | Technological–operating part – list of indicators

Indicator	Factors
Scope of the water treatment technology	Treatability index Separation efficiency Legislation Frequency of non-complying analyses of produced drinking water
Pump technology	Age Failure rate Position of the working point Efficiency
Measurement, monitoring and manipulation	Measurement of hydraulic quantities Measurement of qualitative parameters Operational handling
Separation technologies	Number of separation stages Process parameters Construction of separation units
Further processes	Pre-treatment Sludge management Undesirable disinfection products Disinfection efficiency
Effectiveness of operation and safety	Internal water consumption Treatment plant operation continuity Available performance of the treatment plant with respect to its design values Operation automation Operation interruption Inadequate output Chemical leakage

The indicator with the highest weighted value in the entire methodology is related to separation technologies. In this respect, an in-depth assessment is necessary, requiring knowledge of the course of the separation process. The assessment requires a detailed analysis of documentation and supporting calculations. Factors are assessed such as 'Process parameters' and 'Construction of separation units', the value of which is selected according to the statements in Table 6.

Water treatment plant assessment methodology is a comprehensive methodology, and therefore the list of assessment factors also contains items such as the performance availability of the water treatment plant in terms of its proposed values, trouble-free operation of the water treatment plant and chemical leakage. These items decidedly contribute to the overall assessment of the plant; however, they have a smaller impact on the result of the assessment.

The complete list of indicators and factors is available in electronic form on the TEAwater website provided below (Technical Audit of Water Distribution Systems 2016).

CASE STUDY

The proposed methodology for assessing the technical condition of water treatment plants was tested on several facilities and is gradually implemented for assessment purposes. The text below presents an example of the assessment of a specific water treatment plant. The name of the treatment plant is not disclosed for obvious reasons.

The assessed water treatment plant forms part of a group of water mains which supply one district town and several smaller towns and municipalities. The water treatment plant was built between 1962 and 1967. In 1996, partial refurbishment was carried out and filters were renovated in 2014. The water treatment plant supplies water to about 14,000 residents.

Two surface water resources are used as raw water resources – both of them are mountain streams. Raw water is therefore extracted from these streams via bottom channels. The water is clear for most of the year with low turbidity and colour values.

Table 5 | Structure of the assessment verdict for selected factors

Indicator	Factor	Score	Description
Scope of the water treatment technology	Legislation	0	Not assessed;
		1	All standard indicators of the quality of drinking water are below the specified limit and no exemption is made regarding the quality of drinking water;
		2	An exemption is made regarding the quality of drinking water or it is expected that after the amendment of the requirements for drinking water, water conforming to the indicator with the threshold indicator (TI) will not be produced;
		3	Some of the indicators with the highest threshold indicator (HTI) reach such values that these values will not be satisfactory after an amendment to legislation.
	Frequency of unsatisfactory results of analyses	0	Not assessed;
		1	The limit values of HTI indicators are not exceeded; TI indicators are exceeded at a max. of up to 1%;
		2	The limit values of TI indicators is exceeded by 1–2%, in HTI indicators up to 1%;
		3	The limit values of TI indicators is exceeded by more than 2%, in HTI indicators over 1%.

Note: Czech law applies two types of limits for drinking water quality. Each of these two limits has a different relation to the quality of supplied drinking water. The threshold indicator (design TI) applies to health non-hazardous indicators such as iron. The second type is the highest threshold indicator (design HTI) which can be interpreted for health hazardous indicators such as arsenic and lead.

Table 6 | Structure of the assessment statements for the selected factors

Indicator	Factor	Score	Description
Separation technologies	Process parameters	0	Not assessed;
		1	The key parameters of separation processes are satisfactory (the values need to be verified, for example, surface load, Reynolds number, filtration rate, retention time, etc.);
		2	The key parameters of separation processes have unfavourable values only in extraordinary situations (such as during short-term increased performance of the water treatment plant);
		3	The key parameters of separation processes are constantly unsatisfactory (values need to be verified, for example, the surface load, Reynolds number, filtration rate and others).
	Construction of separation units	0	Not assessed;
		1	The technical equipment in which separation processes are taking place is fully satisfactory in terms of construction (such as adequately constructed inlet and outlet, appropriate raking device, working pump with adequate performance);
		2	The technical equipment in which separation processes are taking place has certain construction defects; however, these have no major impact on the quality of water at the outlet from the equipment;
		3	The technical equipment in which separation processes are taking place has major construction or other defects that have a noticeable impact on the quality of water at the outlet from the equipment.

Raw water from the surface water resources supplying the water treatment plant is classified by the operator as category A1 according to the relevant decree. (*Note:* Czech law specifies three raw water quality categories – A1, A2 and A3.)

The quality of raw water is regularly checked as part of monitoring and operational analyses. It must be noted that the monitoring and operational analyses cannot capture all the qualitative conditions of the raw water due to their limited frequency and extent. The water treatment plant is not fitted with measuring equipment to measure the quality parameters of the raw water and there is no basic technology here. The quality of raw water is checked daily by the operational staff of the water treatment plant only by checking the water surface in the water intake structure.

According to the results of the monitoring and operational analyses, the physical and chemical parameters of the quality of the raw water under normal flow conditions are below the valid conditions for drinking water.

The raw water shows a considerably variable microbiological and biological composition depending on the season of the year, temperature and flow conditions. In microbiological terms, the raw water contains coliform bacteria, isolated intestinal enterococci, *Escherichia coli* and isolated *Clostridium perfringens*. The water is most likely subject to faecal exposure as microbiological contamination fluctuates depending on the flow conditions.

The operational records show that the water level and flow-rates in the resource water streams often fluctuate during the year depending on the current weather conditions. On average, sludge conditions occur in the water four times a year, while the physical and microbiological limit values of water quality indicators are exceeded significantly. Results of the water analyses show that there is a regular significant increase in coliform bacteria up to uncountable values. Given the deteriorating raw water quality during the turbidity conditions there are regular accidents at the separation structure, resulting in necessary operation downtimes.

Technological line

The technological line, dating back to the 1960s, is based on simple physical treatment. The protected output of the water treatment plant is 55 $l.s^{-1}$, the average output is currently about 28 $l.s^{-1}$.

Raw water from the surface resources flows into one sedimentation tank (without a sludge scraper system), then flows through three open high-speed filters filled with sand and equipped with drainage pipes. Finally, the water is disinfected with chlorine gas and stored in two storage tanks arranged one behind the other. Flow through the plant is gravitational and no chemicals besides chlorine gas are dosed (not available or possible). The plant is equipped with a measurement system metering the filtration level, flow-rate through the plant and concentration of free chlorine. The sludge water is conveyed to a sludge field located close to the plant. Before refurbishing the sludge field, the sludge water was discharged into the receiving body of water, which was unacceptable.

Failure rate

The plant's failure rate was analysed on the basis of the failure records kept by the plant's operator. The records were available for the period of 10/2014–03/2016, i.e. for 18 months. In the monitored period, 22 various failures were recorded such as: three failures of the chlorine equipment, of which one was related to a chlorine leak, failure of the closing valve, non-functional pump, defect in a tank, filter failure, etc. Based on the available records, it can be stated that the failure rate is within normal limits given the age of the plant.

Evaluation

The technical condition of the plant was assessed in terms of the structural condition and technological operation while considering all the technical condition indicators listed in Tables 1 and 4.

What can be considered as highly risky is the fluctuating quality of raw water, which is not really monitored in any manner other than visually by the operating staff (although daily). The problem is that this concerns indicators of fecal contamination and, to a smaller extent, the aggressiveness of water. Assessment of the technical condition is primarily affected by the unsatisfactory scope of the technology in view of the quality of raw water, the condition of separation units and their low efficiency during sludge conditions, as well as inadequate operation of storage tanks, and the absence of equipment for continuous monitoring of at least the basic raw and drinking water quality indicators. Despite its age, the structural condition of the plant is rather good.

Based on the validated facts and detailed inspection of the plant, an assessment was made according to the aforesaid methodology. The most corresponding statements

Table 7 | Valid statements for selected factors

Indicator	Factor	Valid statement	Factor assessment
Measurement, monitoring and manipulation	Measurement of qualitative parameters	Key qualitative parameters are not measured during water treatment or at the plant outlet	3
	Operational manipulation	The operating staff of the water treatment plant can change the plant output in abrupt steps only or the current quality indicator values are not taken into account when dosing chemicals	2
Separation technology	Process parameters	The key parameters of the separation processes have negative values only in extraordinary situations (such as during the plant's short-term increased output)	2
	Construction of separation units	The technical equipment in which the separation processes take place shows crucial structural or other defects which have a noticeable impact on the quality of water at the plant outlet	3

applying to the technical condition were selected at the level of the individual factors. Table 7 shows the valid statements for the assessed plant in relation to selected factors concerning 'Measurement, monitoring and manipulation' and 'Separation technology' indicators.

Based on the valid statements related to the individual factors and the corresponding point assessment (on a scale of 0–3), aggregation was also carried out in the direction of higher assessment levels. That is, the scores were counted for the individual indicators and subsequently for the key components and the plant as a whole. Table 8 provides a summary of the assessment at the level of indicators and the civil structures.

The overall technical condition of the water treatment plant according to the described methodology is assessed at C+ level. It must be pointed out that the assessment of the technical condition applies to the civil structure, which is operated in the given manner as a whole. The method of determining the resulting assessment using multi-criteria assessment techniques is described in detail by Tuhovčák *et al.* (2016).

Table 8 | Assessment summary

Part	Assessment of part	Indicator	Aggregate assessment
Structural–technical part	B	Condition of the civil structure	3
		Conditions of the technological elements	2
		Protection of the plant against ambient effects	3
Technological–operational part	C	Scope of water treatment technology	3
		Pumping technology (treated water pump station)	2
		Measurement, monitoring and handling	4
		Separation technology	4
		Other processes	2
		Effectiveness of operation and safety	2
Total assessment of the water treatment plant	C +		

CONCLUSIONS

The described assessment methodology for water treatment plant technical equipment forms a part of the comprehensive methodology for the assessment of entire water supply systems (water intake structures, pumping stations, tanks, etc.). Development of the methodology for a water treatment plant (TEAT Module) was not simple, because a water treatment plant contains a high number of various elements including structural, technological and electronic ones.

In addition, each of the over 3,000 water treatment plants in the Czech Republic is unique. Therefore it is difficult to adopt some universal assessment rules where the entire assessment role could be generalised. Despite this, the assessment methodology was developed and its outputs can serve as a basis for comparative analyses, planning of repairs, refurbishment, preparation of refurbishment financing plans or as a basis for further detailed structural and technological surveys, etc.

The proposed methodology can interpret the technical condition of the assessed infrastructure and above all draw attention to the critical points in the system of drinking water production. The output from the assessment of the technical condition using the described methodology is of practical importance to the owner and operator of the water supply infrastructure, who are often aware of the problematical parts of the operated systems; however, only an objectivised output supported by an assessment methodology can be a convincing argument when planning repairs, reconstruction or more extensive investment projects.

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