SAFETY OF THE WATER SUPPLY SYSTEM IN THE ABSENCE OF DESINFECTION RESIDUE

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The paper focuses on the drinking water supply with public water mains without the use of disinfectant residues in the transported water. This method of delivering drinking water can only be considered if a sufficient number of functional barriers are present in the distribution system to prevent the penetration of pollution into the transported water. One of these barriers is, for example, a good technical condition of the water-supply system. The security of water supply without disinfectant is ensured by an initial assessment of the suitability of the water system for this mode of operation, risk analysis and network monitoring in selected critical points of the system.

KEYWORDS
chlorine, disinfectant residue, water supply, undesired event, risks analysis

1 INTRODUCTION

Objective of the public water supply systems operators is to supply drinking water to the consumers in the required quantity and quality to meet the requirements stipulated by the Decree No. 252/2004 Coll., which sets drinking water limits in the Czech Republic. By applying the chlorine-based chemical disinfection and maintaining sufficient residual chlorine concentration in the distribution network, combined with other measures and actions, drinking water supply in the required microbiological quality should be ensured. However, research and experience from practice bring many new insights into functioning of the chlorine-based chemical disinfection. Often the negative aspects of chlorine-based chemical disinfection are mentioned, especially the undesirable influence on taste and odour, the emergence of so-called disinfection by-products, and, last but not least, the counterproductive use of too small dose of chlorine to maintain the disinfection residue, which can cause inactivation of only indicator micro-organisms. European and national legislation of individual Member States set microbiological and biological limits for the occurrence of so-called "indicator organisms" in drinking water. So, not all the microorganisms are observed in the distributed water, but only a few selected representatives. Unfortunately, some of these indicator organisms are significantly sensitive to chlorine. Thus, the low chlorine concentration in the distributed water can only inactivate the indicator organisms. Other micro-organisms that are less sensitive to chlorine may remain in drinking water. This can mask existing problems in the water supply system. Switching to drinking water supply without the use of disinfectant residues requires a gradual reduction of the chlorine dose. Prior to the first reduction in chlorine dose, the primary assessment of the water supply system shall be carried out to determine whether it is suitable for this mode of operation. The technical state of the water mains, the presence of safety barriers in the water supply system and their functionality are also assessed. Concept of more barriers (multi-barrier approach) ensures safety in case of failure of any of these barriers. The barriers include protection of the water source, multiple steps in water treatment and proactive management of the distribution system. When it comes to the question whether or not chlorine is irreplaceable in drinking water for human health protection, it can be noted that there are relatively little data confirming that the residual disinfectant in the distribution network would prevent outbreak of infection from drinking water. [Rosario-Ortiz, 2016]. Switching to drinking water without the use of a disinfecting agent takes place gradually. It is a controlled process that is accompanied by detailed monitoring. Process security is determined using a risk analysis. For example, the previously developed WaterRisk methodology can be used.

2 ADVANTAGES AND DISADVANTAGES OF DRINKING WATER SUPPLY WITHOUT A DISINFECTANT

Advantages of operation of the water supply network without use of chemical disinfectants are as follows:

- By-products of disinfection, such as carcinogenic trihalomethanes (THM), do not occur in drinking water. Halogen phenols, resulting in customer complaints about chlorine flavour and chlorine odour of water, do not occur either. For example, omission of chlorine dosing in Amsterdam led to reduction of THM value below the limit of detection. [Kooij, 2014]
- Masking of microbial contamination of the drinking water cannot appear, as documented during operation with application of a disinfectant. When the disinfectant is used, even very low concentrations of free chlorine cause inactivation of the indicator coliform bacteria and E. coli, as these organisms are very sensitive to chlorine. For instance E. Coli is reduced by 99 percent as early as at the concentration of 0.05 mg/l. [Payment, 1999; Vostrcil, 1999] After addition of the disinfectant, these indicator organisms may be inactivated during the contamination event, whilst the other, more resistant pathogens may still be present. [Kooij, 2014]
- The disinfectant can react with biofilm (material, biofilm material), but cannot react with bacteria. The disinfectant residue can support re-growth, namely by reacting with organic compounds contained in water and producing more readily biodegradable compounds. [Kooij, 2014]
- When disinfecting agents are applied, the nitrates can be converted into nitrites. Possible explanation is that the reduction of nitrite levels may be due to the action of nitrifying bacteria that are apparently able to better convert nitrite to nitrate in a chlorine-free environment. The rate of this conversion depends on other influences such as water temperature, pipe material. [Hampl, 2010]. Nitrates at higher concentrations in drinking water cause methemoglobinemia. Decree No. 252/2004 Coll. establishes the highest nitrite limit in drinking water of 0.50 $mg \cdot l^{-1}$, for nitrates a maximum limit of 50 $mg \cdot l^{-1}$ is set. Nitrates are harmful indirectly. In the gastrointestinal tract, bacterial activity can be reduced to more toxic nitrite. [Pitter 1999]

Disadvantages of operation of the water supply network without use of chemical disinfectants are as follows:

- Presence of adequate concentration of disinfectant may reduce the risk of secondary microbial contamination, which can penetrate into the network through the failures,

- repairs or water backflow. It may affect re-growth of mainly coliform bacteria and colony counts [Kooij, 2014]
- Presence of disinfectant residue may indicate a system failure. If the network is monitored for concentration of the disinfectant residue, measurement of the reduced concentration of the disinfectant residue may be a signal for a contamination event that has occurred. [Kooij, 2014]

Whether or not and to what an extent advantages or disadvantages of the disinfectant are reflected in drinking water depends mainly on the site of dosing and on the amount of the dispensed disinfectant. When considering use of a disinfectant, there is no simple answer to the question of whether the residual chlorine is necessary and beneficial for health and healthy quality of drinking water. The answer naturally also depends on water quality entering the network, on hydraulic and building integrity of the network, and on the ability to apply good hygiene practices for the supplied drinking water. [Kooij 2014]

3 INITIAL ASSESSMENT REGARDING TRANSITION TO DRINKING WATER SUPPLIES WITHOUT ANY DISINFECTANT

By discontinuing chemical disinfection, the water supply system loses one of its security barriers. It is important to assess whether or not the system is suitable for operation without any disinfectant. The assessment is particularly important for small water supply systems operated by a small operator or a municipality. It has to be considered what failures in water quality ("the undesired events") may occur when switching to supplies of drinking water free from any disinfectant, and what factors affect them. The effort is to cope with this process of transition so that possible disruptions in water quality may be avoided. Before the operator begins to consider water supply without any disinfectant, the water supply system should be subjected to the initial overall analysis of whether it is suitable for this type of operation at all. The first assessment also includes simulation of chosen indicators of drinking water quality in the water supply network. [Kovar 2014] Analysis of the water supply system is based on the following assessment:

3.1 Water source

An underground source not affected by surface water is most suitable for operation without a disinfectant. Compared to surface water, the groundwater has an almost constant temperature throughout the year. Groundwater does not need not be treated complexly, because the soil and the rocks above it fulfil the function of a filter and therefore in the majority of cases the water meets the microbiological and biological quality (according to the Decree No. 252/2004 Coll.) and the related overall biological stability. Coliform bacteria or E. coli present in groundwater, or a higher content of organic substances in water, indicate penetration of surface water or pollution that is usually of anthropogenic origin. It is important for non-disinfectant operation that the water source may contribute to the multi-barrier approach to protection of network operation and that its barrier may be effective. Proper barrier functions are achieved if, for example [Rajnochova 2017]:

- Functional protective zone of degree I, which prevents unauthorized persons and animals from entering, is achieved by high-quality fencing, by secured access to the source (hood, etc.). Protective zone of degree II, where the requirements of § 30 of the Act No. 254/2001 Coll., on waters, (as amended), are observed, minimization of livestock grazing and farming round the source, etc.
- Appropriate protection of the water source and its collection, well-made back-filling of the collecting devices, no turbidity events occur.
- Sufficient depth of the collecting device guaranteeing that water quality may not be affected by surrounding soil loss by splash (surface water effect), confined groundwater level.
- Good civil part condition, rodents, earthworms, insects, fallen leaves, etc. may not penetrate.

If the source meets these conditions, its functional barrier protecting it from contamination may be assumed. Functionality of the barrier should be confirmed by comparing with results of microbiological analyses performed during the last 2 to 3 years. If affection of the underground source by surface water (wash during rainfalls) is confirmed and the operator is interested in operation of the water supply network without chemical disinfection, replacement of chemical disinfection for UV radiation can be considered.

3.2 Water treatment plant (WTP)

If a water treatment plant (WTP) is the integral part of the water supply system, this plant should also have a functional barrier and contribute by its reliability to the multi-barrier protection of operation. A reliable barrier of the water treatment plant and its storage facilities is created by the following combination [Rajnochova 2017]:

- Protection of WTP from penetration of unauthorized persons, game, rodents, insects, etc., (Figure 1)
- Regular cleaning of all areas (disinfection of floors, removal of webs, etc.),
- Installation of doorsills to prevent dust, pollen, plaster and other impurities from entering the free level of the storage tanks filters, resulting in formation of biofilms and sediments in the storage facilities,
- Water circulation, avoiding dead corners,
- Regular cleaning and disinfection of storage tank walls, filters and their refilling,
- Good technical condition of the storage tank, especially its sealing, preventing leakage of surface water in case of rainfalls,
- Reliably working vent holes preventing mould formation, protection of these vent holes, especially in the storage and filter zone, from insects, pollen and dust,
- Avoiding penetration of solar radiation into the filter and storage zones,
- Filter washing should be determined, based on hydraulic losses on the filter,
- Filtering should be done under simultaneous measurement of the water turbidity at the outlet,
- Staff training, good hygienic habits of the staff (clean clothing and footwear to avoid bringing impurities from the outside), state of health of the staff in terms of infectivity, etc.

If the water treatment plant and storage facilities meet these conditions, a functional barrier protecting them against contamination can be assumed. Functionality of the barrier should be confirmed by comparing with the results of microbiological analyses performed during the last 2 to 3 years.

3.3 Distribution network

Distribution network with relevant structures, such as water reservoirs (WR) and pumping stations (PS) is another part of the multi-barrier protection approach. Reliable barrier of the distribution network and its structures is created [Rajnochova 2017]:

- Adequate overpressure in the network (higher than 0.05 MPa) without any significant fluctuations,
- Low failure rate of the network (less than 0.2 failures·km·year^{-1}),
- Low water loses,
- Proper operation of the distribution system by the qualified staff,
- Adequate pipeline speed (> 0.5 m·s^{-1}) preventing stagnation of water, formation of biofilm and development of microorganisms.

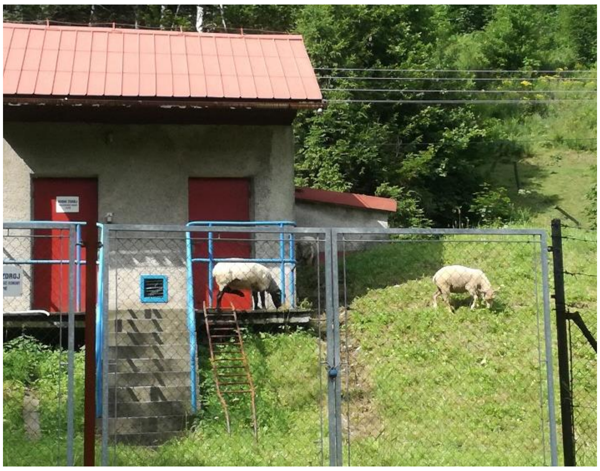

Figure 1. Corruption of the security barrier of the reservoir storage tank. In case of failure of the horizontal ceiling insulation of the tank, contamination of drinking water can result in faecal pollution.

The same requirements, like for WTP with storage facilities, see above, are applied for the network structures such as WR and PS. The internal distribution line of the consumer is the final place, where quality of transported water may be deteriorated. If the aforementioned conditions are met, it can be assumed that the system is operated with the multi-barrier protection approach and is suitable for non-disinfectant operation, which in fact should be confirmed by comparing with the results of microbiological analyses of the last 2 to 3 years. A detailed description is contained in the German strategy for transition to water supplies without any disinfectant [Korth 2004].

Figure 2. Safety barrier violation of the water distribution network. Insufficient technical condition of the pipeline. When pressure drops in the water supply network, penetration of environmental pollution into the water pipe may occur.

Figure 3. Insufficient technical condition and inappropriate construction of the water treatment plant. Large solar windows transmit the sunlight to the surface of the treated water, which promotes the growth of green algae in the treated water.

4 SAFETY OF THE WATER SUPPLY SYSTEM IN THE ABSENCE OF DESINFECTION RESIDUE

The safety of the water supply system is determined by risk analysis using the WaterRisk methodology. This methodology defines undesirable events that may occur either during the operation of the water system without the use of disinfecting agents, or during the transition process. Under the undesired event (UE) [Tuhovcak 2010] we shall understand the condition when the system (structure, system element, and product) loses its desired feature or ability to perform the requested function. The undesired event is accompanied by occurrence of undesired consequences and is always defined for a particular element of the system. The undesired event is, in principle, a failure, i.e. water quality failure in this case. The general WaterRisk methodology and methodology of Water Safety Plans elaboration were used to describe (determine) UE and factors. [Tuhovcak 2010]

Three main undesired events that may occur have been defined for the process of transition to supplies of drinking water without use of any disinfectants, namely as follows:

- UE 1- Increased count of colonies at 22°C and 36°C,
- UE 2 - Occurrence of coliform bacteria,
- UE 3 - Occurrence of E. Coli bacteria.

4.1 UE 1-Increased count of colonies at 22°C and 36°C

The count of colonies is understood a group of the so-called heterotrophic (organotrophic) bacteria, needing a carbon source from organic substances for their growth. It is an indicator of microbiological recovery of drinking water. This indicator does not provide any direct evidence of pathogenic germs presence and its increased value in water is not connected directly with threats to human health. [Kozisek 2014]

The factors that can affect the increased count of colonies are as follows [Rajnochova 2017]:

F 1.1 – Formation of biofilm

F 1.2 – Biological stability of water

F 1.3 – Water hold-up time in the network

F 1.4 – Presence of sediments at the bottom of the pipeline

F 1.5 – Concentration of free chlorine before discontinued dosing

F 1.6 – Water temperature

4.2 UE 2 – Occurrence of coliform bacteria

Total coliform bacteria are the bacteria commonly present in an environment, such as soil and vegetation. They are generally harmless. If presence of only the total coliform bacteria is detected, the natural environment is most likely their source. Faecal contamination is improbable in this case. However, if natural pollution could penetrate into the system, pathogens could appear here as well. It is therefore important to find and investigate the source of contamination.

The factors that may affect occurrence of coliform bacteria are as follows [Rajnochova 2017]:

F 2.1 – Impairment of physical and hydraulic integrity of the water supply system

F 2.1 – Water temperature

4.3 UE 3 – Occurrence of E. Coli

The E. coli indicator bacteria is a subset of coliform bacteria. In most cases it is completely harmless. However, there are also pathogenic strains (e.g. Escherichia coli O157: H7) [Kozisek 2006] Presence of E. coli in drinking water is an indicator of fresh faecal contamination. E. coli is very sensitive to chlorine, even a very low concentration of residual chlorine can inactivate it. [Payment 1999] The factor influencing occurrence of E. coli is as follows:

F 3.1 - Impairment of physical and hydraulic integrity of the water supply system.

The probability of an undesirable event is determined by the point assessment of the individual factors that influence the occurence of a particular UE. By compiling the risk matrix, ie the probability of UE and its consequences, it is possible to assess the risk of an undesirable event, ie a water quality failure.

5 CONTROL ALGORITHM OF THE PROCESS OF TRANSITION TO OPERATION WITHOUT USE OF A CHEMICAL DESINFECTANT

The algorithm, controlling transition to supply without use of a chemical disinfectant, consists in assessment of water analyses for the last 2 to 3 years. If microbiological abnormalities did not occur in the analyses in the past, a preliminary survey programme lasting for at least 2 months will be commenced. If microbiological abnormalities do not occur in the preliminary survey programme, dose of the disinfectant will be decreased gradually by ca 0.1 to 0.15 $mg \cdot l^{-1}$. The surveillance programme then follows for 2 months as a minimum. Occurrence of water quality failures is monitored at this stage, see the undesired events shown above. If undesired events do not occur, dosage of the disinfectant can be discontinued completely. And again, it is necessary to perform the surveillance programme for at least 2 months. If neither any microbiological abnormalities nor undesired events occur at this stage, it can be stated that disinfectant dosing can be discontinued permanently. [Korth 2004; Rajnochova 2017]

The decision algorithm, controlling transition to supplies of drinking water without use of disinfectants, is based on the German strategy, stipulating 3 possible methods of system operation. The first method is drinking water supply in absolute absence of disinfection, both chemical and physical. This is possible only if a well-protected underground source is available. The assumption is that water enters into the distribution system complying with the microbiological and biological requirements stipulated by the Decree 252/2004 Coll., and the network does not provide suitable conditions for re-growth. The second option is to eliminate additional chlorination. This can only be realized if water after disinfection meets the microbiological requirements, and the network has such conditions regarding water flow rate, amount of sediments, concentration of biodegradable carbon, etc., that there is no need to maintain the disinfectant residue. The last option is to replace chemical disinfection for the UV disinfection. [Korth 2004]. This solution is most frequently chosen in the Czech Republic.

6 CASE STUDY KATERINICE VILLAGE – THE FIRST ASSESSMENT

The water supply system of the village of Kateřinice is a case study where a primary assessment of the drinking water supply system has been made, whether it is suitable for switching to operation without the use of a disinfectant. It is a small simple public water supply system operated by the municipality itself.

6.1 Water source

The system is supplied by a surface water source. Raw water abstraction is done by two wells at a depth of 3 to 6 meters. The device does not reliably perform the function of the security barrier because of poorly executed gravel wall of the well. As a result, heavy rains penetrate the massive turbidity from a water source into a water treatment plant. In this way, microbiological contamination could also penetrate the water treatment plant, which could leak into the water source by leaping out of the surrounding areas.

The functional barrier of the source is a first-degree protection zone. There are neither agro-cultivated areas in the vicinity of the flow, nor anthropogenic influence is expected. The source is surrounded by fencing. However, wildlife access is allowed here in the immediate vicinity of the stream, and contamination of the source of water can occur through the bite of excrement.

It can be stated that the only resource safety barrier is the first-degree protection zone. Assuming the repairs of the collection device and the appropriate choice of water treatment technology, the source barrier could be considered as satisfactory.

6.2 Water treatment plant and accumulation

This is a simple single-stage water treatment plant, which consists of only three slow sand filters. The water treatment is secured only by fencing and locked door. The access to the filters is ensured by a steel bridge which is strongly corroded. A fan is malfunctioning in the wall, there is no safe air filtration. In the filter unit space there is visible collapsing concrete of the partitions and the protruding reinforcement damaged by corrosion. Corrosion also attacked a metal feed chute. Presence of open sand filters provide a greater risk of secondary contamination than pressure filters. The filtration process cannot remove the frequently occurring turbidity events and the small particles from the water source then penetrate into the water supply network. Washing of the filter is not performed on the basis of hydraulic loss. Introducing of filters after washing is not determined on the basis of turbidity measurement but based on the estimation of the technician. In the area in front of the accumulation tank (corridor) there is visible faded plaster. Also a door frame, a ladder and a chemical holder are strongly corroded. The entry into the storage tank is missing a doorsill which can lead to penetration of pollutants into the free surface, such as dust, pollen, corrosion particles, plasters, webs, etc. There are sediments on the bottom of the storage tank and a visible biofilm on the walls. The dosage of sodium hypochlorite is performed in the reservoir storage tank by estimation only.

It can be stated that the barrier of the WTP consists only of fencing and locked entrance. To improve the barrier to be functional, efficient and contributing to the multi-barrier system of protection, the water treatment plant should be reconstructed.

At present, the barrier of the water treatment plant cannot be considered as functional and efficient because of the possible risk of microbiological or biological contamination from multiple sites and insufficient water treatment.

6.3 Water distribution network

The water pipe material is uniformly PVC DN 150 and DN 80 in the whole network. The total length of the water main is 8.57 km. Controlled flushing of the pipeline was carried out only once, in 2013. The age of the water supply network is around 30 years, which corresponds to its relatively good technical condition. The pipeline is oversized, stagnation of water in the pipeline, the development of biofilm and bacteria proliferation may occure. The problem is also a sedimentation of fine particles that penetrated into the water supply through imperfectly working filtration units in the water treatment plant. According to the hydraulic analysis results, the retention time of the water in the network is above 24 hours. The average water velocity in the pipeline is 0.07 $m \cdot s^{-1}$ in the upper pressure zone and 0.03 $m \cdot s^{-1}$ in the lower pressure zone during the maximum daily flow rate. Customers sometimes complain of turbidity and water smell. Water losses in 2015 account for 28% of the rewenue water. Pressure conditions in the network are stable, there is no great pressure fluctuation. The failure rate in 2012 was 0.06 $failure \cdot km^{-1} \cdot year^{-1}$ which is very low value. It can be stated that the barrier of the distribution network works properly. The only imperfections are a very low water flow rate and a slightly increased water loss that can be caused by pipe leaks.

6.4 The first assessment

Based on the assessment made, it can be stated that the water supply system of Kateřinice municipality does not have sufficient multi-barrier protection. Therefore, it is not possible to dispense with chemical disinfection with sodium hypochlorite as this disinfection creates at least little protection against contamination with microbiological contamination. The technical condition of the water treatment plant is problematic. Reconstruction is also needed for gravel wall of the water source.

7 CONCLUSIONS

The paper is focused on the possibility to operate drinking water distribution without application of any chemical disinfectant. The fact that foreign chemicals of disinfectants, which - under some circumstances - may create toxic by-products of disinfection, are not brought into drinking water is the undisputed advantage of operation without a disinfectant. Reaction of chlorine can result in conversion of high-molecular natural organic compounds into simpler substances serving as a substrate for bacteria.

Next, the paper describes the process of first assessment of water supply structure to determine if the water supply structure is suitable for the application of the disinfectant-free operation. Moreover, three undesired events, which may occur with ending of dosing of disinfectant, were determined. Three major undesired events have been defined: UE 1 - Increased count of colonies at 22°C and 36°C, UE 2 - Occurrence of coliform bacteria, and UE 3 - Occurrence of E. coli. Occurrence of coliform bacteria and E. Coli has been broken down into two undesired events, because the coliform bacteria are restricted by the Decree by the limit value only, i.e. be exceeding it, water loses the respective quality, but water supply is not interrupted, whereas if the limit value is exceeded in case of E. Coli, which is subject to the highest limit value, water supply must be interrupted unconditionally and an alternative drinking water supply source must be ensured. Also the factors have been determined that affect these undesired events occurrence. By using the WaterRisk methodology, the risk of this method of operating the water supply system and the likelihood of occurrence of an undesired event can be determined. The first assessment process was applied to the water supply system in village Kateřinice. It was determined that this water network does not meet the necessary requirements for the application of the disinfectant-free approach, particularly the multi-barrier protection of water supply system is inadequate. Therefore, the analyzed approach of disinfectant-free water supply cannot be used in this distribution system.

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