Design of a Water Treatment Plant with the Support of Laboratory Models

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Abstract

The subject of the research focused on the possibilities of supporting the design of surface water treatment plants using laboratory models. Within the pilot study, the possibilities of using different water treatment processes in the treatment of water from the water reservoir Nové Mlýny in the Czech Republic were assessed. The planned treatment plant is to supply a future recreational site from a shallow reservoir with significant eutrophication and chemical industry in the drainage basin. Coagulation, sedimentation, dissolved air flotation, membrane filtration processes and adsorption on granular activated carbon were investigated. These processes were identified by the preliminary study as applicable to water treatment and it was necessary to determine which could be applied given the site conditions. Laboratory models for the individual processes were used during the laboratory testing. During the research, problems encountered were debugged and the models were modified and some extensions were added to the original models. The coagulation and sedimentation processes were investigated using conventional jar tests. The dissolved air flotation process was simulated using a modified jar test and a lab scale model. Different types and doses of coagulants, mixing parameters and residence times were investigated in the tests. Turbidity value was used as an optimization parameter due to its rapidity of determination and low cost. For some tests, potassium permanganate oxidizability (also known as the permanganate index) was also used as an evaluation parameter so that different evaluation parameters could be compared. In addition, for the dissolved air flotation process, the parameters of the produced sludge - its quantity, suspended solids content and chemical oxygen demand - were monitored. These parameters are crucial for discharge of waste water into the sewer and its costs. The adsorption tests on granular activated carbon were performed as batch tests. The evaluation parameter was the manganese index. Another possible variant of activated carbon tests is a continuous flow-through column. These columns also allow monitoring of the process of fouling and the evolution of the effluent over time. The pilot project then used the results of the laboratory tests to create a design for a treatment plant in the area of interest and selected parts of the project documentation. The pilot project demonstrated the usefulness of laboratory testing as a tool to support the design of drinking water treatment plants. At the same time, these tests allow for a faster and more certain identification of the appropriate water treatment technology and thus reduce the extent of semi-operational testing at the site, leading to a more efficient use of funds by investors.

Keywords: case study, water treatment plant, laboratory models, turbidity

Introduction

Water is the basic source of life and its cleanliness is key to ensuring health and the environment. Today, tightening legislation requires changes to existing treatment plants and the introduction of new technologies. Similarly, resource scarcity is leading to the use of water sources that were previously not planned as drinking water sources due to their high pollution levels. Water treatment processes are therefore necessary to remove various pollutants and micro-organisms from water. In order to effectively design and optimize these processes, experimental research on laboratory models is needed. Semi-operational site trials can then be carried out. Only in this way can it be guaranteed that the proposed technologies will be able to reliably and effectively remove pollution from raw water.

Laboratory models make it possible to simulate these processes under controlled conditions and study their efficiency and effectiveness. They make it possible to optimise water treatment processes and achieve greater pollution removal with less chemical and energy consumption.

In this article, we focus on the principles and applications of laboratory models in simulating coagulation and sedimentation, flotation and adsorption on activated carbon. We discuss in detail the characteristics of these processes and show how laboratory models can be used to optimize and improve them.

New European Directive

The first single European Directive for drinking water was issued in 1980 (Council Directive 80/778/EEC). In 1998, Directive 98/83/EC was issued, which is the basis for the current national legislation. This Directive underwent one major amendment in 2015.

After 22 years, it entered into force at the beginning of 2021, the new European Council Directive 2020/2184 on the quality of water intended for human consumption [1], which includes a number of changes for the water sector. The changes concern several areas [2] – risk management of drinking water supply systems, public information on water quality, the assessment of water losses and, last but not least, water quality drinking water. Specific changes concern, for example, the introduction of the 'traditional' indicator turbidity, but new drinking water quality indicators in the category of micropollutants, which will have to be monitoring and elimination in the production of drinking water. The new requirements based on the European Directive will have to be introduced into national legislation [6, 8] and, after a transitional period, also implemented in practice. In addition to the indicators that will be newly incorporated into the legal requirements, there are other pollutants that are monitored with caution, such as microplastics or drug residues.

Turbidity

The new Directive significantly tightens the water quality requirements for the indicator turbidity. Until now, Czech (and Slovak) legislation [4, 5] sets the limit value of turbidity in drinking water at 5 NTU (or ZF).

Now, 95% of the samples taken must not exceed 0.3 NTU and none of the samples must exceed 1 NTU. A further change is the introduction of a frequency (see Table 1) with which turbidity must be monitored in operational analyses depending on the amount of water produced per day.

Tab. 1. Frequency of turbidity analysis according to Directive 2020/2184.

Volume of water produced per day [m^3]	Prescribed frequency of measurements
≤ 1 000	Weekly
1 000-10 000	Daily
>10 000	Continuously

Watch list

One of the innovations brought by the new European Directive is the watch list of substances and compounds of concern for water intended for human consumption. Substances on this list will be monitored and a decision will be made on whether to set a limit value based on the data collected. The list includes a guideline value for these compounds. Monitoring of two hormonally active substances, 17-beta-estradiol and nonylphenol, was introduced in January 2022. Microplastics, which have been the subject of discussion for several years, should be added to the list in 2024.

Micropollutants

Micropollutants as a broad group of substances [3, 7] have been an established type of water pollution for some time already. Micropollutants are found in both surface water and groundwater, of course they also occur in drinking water at very low concentrations, from micrograms to nanograms per litre. They are both organic and inorganic substances of anthropogenic origin. They come from industrial processes, from pharmaceutical products for human use and from veterinary drugs, they are part of personal care products. The introduction of micropollutants into the environment occurs during everyday human activities, and the main routes of introduction are: wastewater, agriculture and industry - (industrial wastewater).

The harmful effects of micropollutants on human health are still debated. Studies analysing the harmful effects of individual micropollutants are very time-consuming and costly. Hygienic limits for drinking water are set by the precautionary principle. In view of the constant development of the state of knowledge, the World Health Organisation (WHO) is continuing to make recommendations, both in the direction of stricter or looser limits. Some substances are already monitored or even banned by European and Czech legislation (e.g. specific pesticides).

Currently, the most frequently mentioned micropollutants [7] are pesticide residues and their metabolites. Other micropollutants include, for example, drug residues or heavy metals. A very current issue is the occurrence of microplastics in the environment, particularly in water and sediment, but more recently also in soils.

New indicators include the PFAS (perfluorinated and polyfluorinated substances). These are completely new type of pollutant indicator in legislation. It is first necessary to know occurrence of these and other substances introduced by the Directive in raw and potable water and, naturally, to know the best available technology leading to the effective elimination of this pollution, so that the hygiene limit can be met.

Experimental Case Study

The water treatment plant, for which laboratory tests of water treatability have been carried out, is planned near the village of Pasohlávky, South Moravian Region, Czech Republic. The water treatment plant would supply a planned recreational area with an annual drinking water demand of around 170 000 m^3.

The source of raw water will be the Nové mlýny I reservoir at the confluence of the rivers Dyje, Svratka and Jihlava. This is the largest water body in the Morava River basin.

The reservoir is shallow, with a depth of no more than 5 m. The average depth is 1.9 m and the average hydraulic retention time in the reservoir is 5.5-9.1 days. The original use was for flood flow reduction, fish farming, recreation and as a source of irrigation water. The storage volume is 3.97 million m^3.

Water reservoir pollution

The reservoir is suffering from siltation caused by erosion of agricultural land in the catchment area. With this related to this, the reservoir is assessed as hypertrophic. The Nové mlýny I reservoir also frequently experiences mass cyanobacterial water blooms. [9]

A known water polluter is the JUBU AG citric acid plant and its derivatives in Austria near Wulzeshofen - the treated wastewater is discharged into the river Pulkava (German: Pulkau), which is the largest right-side tributary of the river Dyje. From this factory, the bulk of the pollution comes from chlorides and sulphates. [10]

The Pulkava is also a source of cyanide pollution - between 2008 and 2010 the average value of the indicator "total cyanide" was 0.026 mg l^{-1} with a maximum of 0.043 mg l^{-1}. In the same period, the value in the Nové mlýny I Dam profile was below the of the method, i.e. 0,005 mg l^{-1}. [11]

Design of water treatment technology

A water treatment process line consisting of coagulation, flocculation, dissolved air flotation, membrane ultrafiltration and adsorption on activated carbon was designed in this order. water disinfection is designed using UV radiation and sodium hypochlorite dosing.

The treatment process designed in this way should ensure reliable production of drinking water even from such a polluted source as the Nové mlýny I reservoir. The process was then simulated by means of laboratory tests so that its efficiency could be verified and design parameters such as the dose and type of coagulant, residence time or type of activated carbon could be determined.

Chalenges of the water source

The catchment area of the reservoir is used for agriculture. Due to the possible presence of pesticides and their residues in the water, the use of adsorption on granular activated carbon is proposed. Adsorption will also improve the sensory properties of the water - its taste and odour.

Another problem is the occurrence of an invasive species of mussel - the Zebra Mussel. There is a risk of clogging of the intake basket by this mussel. Therefore, the study recommended a suction basket with pneumatic rinsing and a special surface treatment to prevent this fouling.

Laboratory experiments for water treatment

Based on the preliminary design, a series of laboratory experiments was proposed.

For the choice of coagulant and determination of coagulation conditions, jar tests based on the methodology of Pivokonsky et al. were used. The advantage of this procedure is the certainty of the determination, where the optimal values found are global optima, not local inflection points. [12]

Three different coagulants were tested in the jar tests. Polyaluminium chloride (PAX 18), aluminium sulphate and ferrous sulphate. The lowest turbidity values were achieved using aluminium sulphate. Coagulation using Pax 18 resulted in increase of chlorides content by 13,7 mg/l. The highest turbidity values in treated water had been observed in case of coagulation by ferrous sulphate (in case of global optimum dosage the turbidity was 0,71 FNU, in case of aluminium suphate the turbidity after optimalisation was only 0,12 FNU). The effect of the volume of the coagulant dose, pH of the treated water, time and speed of fast and slow mixing were monitored during the tests. Based on these values, the volume of the tanks in the treatment plant can then be designed. The effects of coagulant dosage (aluminium sulphate) on turbidity in case of different raw water pH is shown in the Figure 1.

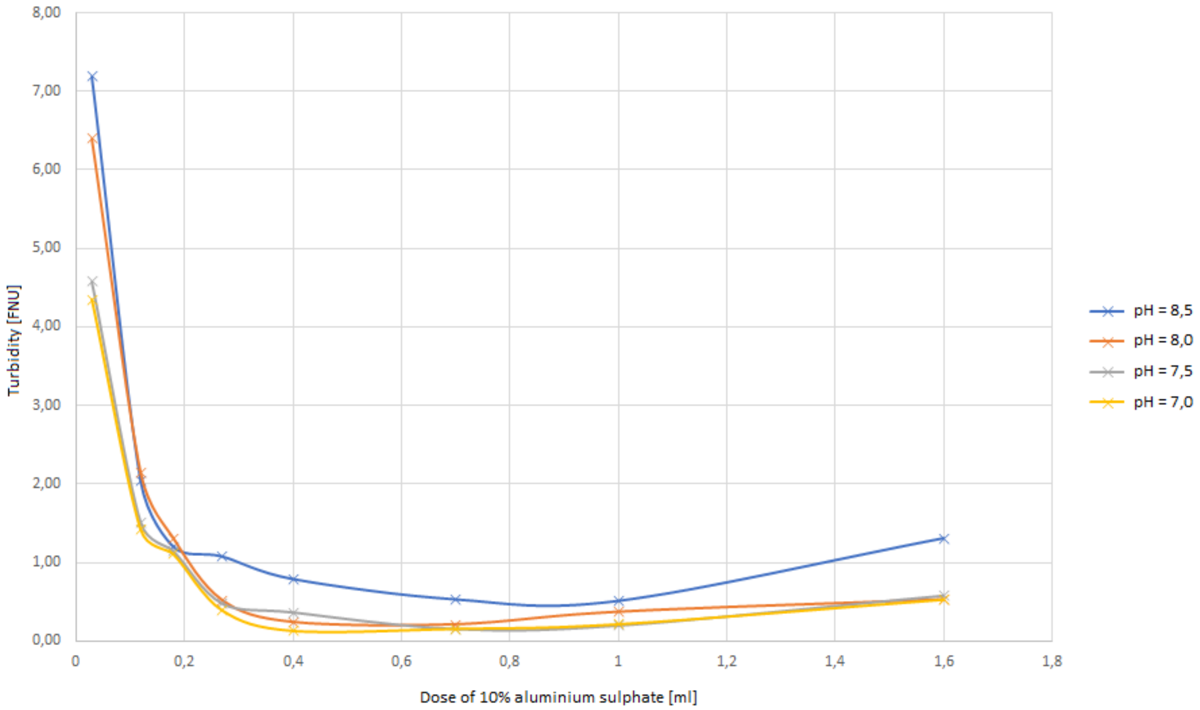

Fig. 1. Turbidity dependency on the dose of 10% water solution of aluminium suphate.

For the flotation tests, modified jar tests were used, where a water saturated with air was injected into beakers after a slow stirring process. The flotation sludge was then examined to determine its sedimentability, suspended solids content and chemical oxygen demand value. These sludge parameters are necessary to determine the disposal options for the sludge, which is a significant operating expense for the treatment plant. Flotation was tested because it may not be a suitable separation process for all types of pollution. [13] Modified jar test setup is shown in Figure 2. The sludge layer is clearly visible.

Fig. 2. Modified jar test setup.

Water treated by coagulation was used for membrane filtration – as in real water treatment plant. For membrane filtration, the membrane fouling process and its effect on the transmembrane pressure were monitored. Furthermore, the turbidity of the filtrate was monitored and found to be constant and within the limit set by the legislation as shown in Figure 3.

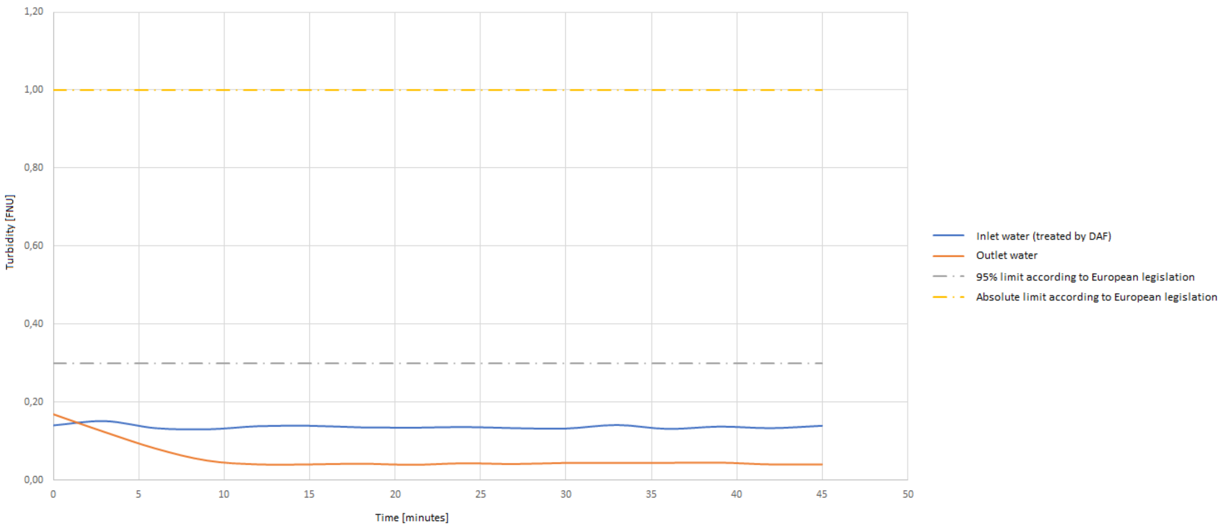

Fig. 3. Time course of turbidity in MF.

Adsorption on GAC was tested in a batch experiment. In it, different amounts of activated carbon were dosed into a pre-measured amount of water treated by previous processes (coagulation, flotation and membrane filtration). Thus, the dependence of the chemical removal efficiency on the carbon dose was investigated. The effect of contact time was not monitored - it was set at 15 minutes. The oxidizability reduction is shown in Figure 4 below.

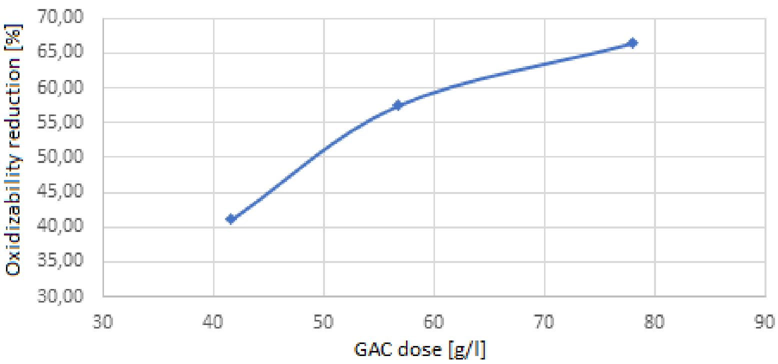

Fig. 4. Oxidizability reduction dependence on GAC dose.

Conclusion

The data from the analysis of the Povodí Moravy, state corporation, were evaluated and the water source was classified as A3 or worse according to the Czech potable water legislation. However, the state analyses do not cover all the parameters set by the Czech drinking water directive, but even the parameters they cover place the source in the A3 category or worse. Between June and September 2022, the water quality of the source was monitored at two reservoir locations so that the influence of the intake location could be assessed. Strong variability in water quality due to the high flow rate of the reservoir was confirmed in both locations. The water quality is also negatively affected by the shallowness of the reservoir and by pollution influx from the catchment area. In view of the pollution pattern during the period under consideration and the possibility of reducing the threat to water quality, a raw water source location approximately 200 m away from the shore, rather than at the shore, is considered as a more suitable intake location.

In November and December 2022, a series of laboratory experiments were conducted to verify the treatability of the water by various technologies – flocculation, sedimentation, flotation, membrane filtration and adsorption. Again, water pollution in the source was high. However, unlike the summer season, the pollution was not so much caused by algae and cyanobacteria, but was caused by sediment flushing from the basin. Water treatibility was also affected by the low water temperature during this period.

A series of laboratory tests were carried out to determine suitable design parameters. A suitable coagulant and its optimum dose were determined, which, based on the analyses performed, appeared to be aluminium sulphate. Polyaluminium chloride (PAX 18) also had a significant effect on reducing turbidity, but its use is not recommended due to the increased chloride content, where the content of chlorides in the raw water is close to the limit for drinking water. The benefits of membrane filtration on water quality have been demonstrated and the advantage of including membrane filtration in the process should be the stability of the turbidity value at the outlet of the treatment plant in full compliance with the new legislation. The adsorption efficiency on GAC was determined by oxidisability (non-specific organic matter). Due to the financial cost, the content of pesticide substances and the effect of adsorption on activated carbon on the reduction of their content was not addressed for GAC filtration.

To further support the proposal, it would be advisable to carry out a similar series of tests in the peak summer season, when the origin of turbidity can be expected to be more organic (algae, cyanobacteria), as opposed to the winter season, when it will be mainly inorganic pollution (runoff from fields). It would also be useful to complement the measurement with the determination of pesticides in raw water and the effect of GAC adsorption on their removal, including longer-term monitoring of pesticide content in raw water.

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