Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2020.25176

186 (2020) 281–289
May

Analysis of the turbidity of raw water in the context of water-supply safety

Dawid Szpak, Barbara Tchórzewska-Cieślak, Katarzyna Pietrucha-Urbanik*

Rzeszow University of Technology, Faculty of Civil, Environmental Engineering and Architecture, Department of Water Supply and Sewerage Systems, Al. Powstancow Warszawy 6, 35-959 Rzeszow, Poland, Tel. +48 17 865 1435;
emails: kpiet@prz.edu.pl (K. Pietrucha-Urbanik), dsz@prz.edu.pl (D. Szpak), cbarbara@prz.edu.pl (B. Tchórzewska-Cieślak)

Received 10 September 2019; Accepted 18 November 2019

ABSTRACT

Turbidity impacts, not only on the aesthetic properties of water but also on many features capable of affecting health. This leaves the parameter in question as a very important indicator of the quality of surface water (due to a large amount of information on potential threats), and one capable of serving as a basis for risk analysis. Information on the turbidity of raw water was obtained from the water-supply company, with the focus being on data from the years 2010–2015. This reflects a research focus on the period following modernization of a treatment plant, completed in late 2009. Variation in the turbidity of raw water through the annual cycle was analyzed, with the finding that no cessation of delivery of water to the city on account of inadequate quality was necessitated. This further denotes a positive assessment regarding the efficiency of the water-treatment technology installed in 2009, which proved to be very effective at treating water whose turbidity changed rapidly from time to time, to reach several thousand NTUs. The paper also details attempts to determine the "a posteriori" probability of occurrence of turbidity of a certain value, in line with Bayesian theory.

Keywords: Turbidity; Probability; Risk; Water safety

1. Introduction

The Water Framework Directive established principles for water-management activity across the European Union. Together with the revised version introduced, the Directive forms the basis for the sustainable use of water resources in the EU Member States. Limit values for priority and pollutant substances are given, with these differentiated in line with the type of water, and with acceptable annual and maximum means set. The regulation on the method of classifying surface water states and environmental quality standards for priority substances defines the methods by which the status of water states is defined, as regards physicochemical, biological and hydromorphological elements, in line with quality indicators for different categories of water states, and with account taken of surface waters of different types. Physicochemical, biological and hydromorphological elements are classified on the basis of criteria expressed as limit values for water-quality indicators, including types of surface water.

The current regulation on the requirements to be met by surface waters used to supply people with drinking water distinguishes three quality categories for surface water:

- Category A_1 - waters requiring simple physical treatment, in particular, filtration and disinfection,
- Category A_2 - waters requiring typical physical and chemical treatment, in particular, pre-oxidation, coagulation, flocculation, decanting, filtration and disinfection (final chlorination),
- Category A_3 - waters requiring highly efficient physical and chemical treatment, in particular, oxidation,

---

* Corresponding author.

Presented at the 14th Conference on Microcontaminants in Human Environment, 4–6 September 2019, Czestochowa, Poland

1944-3994/1944-3986

coagulation, flocculation, decanting, filtration, adsorption on activated carbon, disinfection (ozonation, final chlorination [1]).

It is assumed that water meets requirements if, at the point of recognition, water sampling on a regular basis with appropriate frequency complies with the following conditions:

- that in 90% or 95% of samples, the limit values for water-quality indicators relevant to a given water-quality category have not been exceeded;
- that, for the remaining 5% or 10% of samples in which the limit values for water-quality indicators have been exceeded:
  - the obtained values of indicators, with the exception of temperature, pH, dissolved oxygen and microbiological indicators, do not differ by more than 50% from the limit values for water-quality indicators,
  - there is no risk to human health,
  - in subsequent water samples taken at regular intervals, the limit values for indicators of water quality are not exceeded.

The assessment does not take account of exceedances of limit values for indicators, if these are the result of floods or other natural disasters or exceptional weather conditions, such as intense precipitation or snow melting, or high air temperatures. This is, however, important in the analysis of incidental events when it comes to risk analysis and assessment for the water treatment process, in turn as part of the revision recommendations [1] and the World Health Organization guidelines [2] regarding Water Safety Plans (WSPs). The main purpose of the WSP is to ensure safe access to water intended for consumption, and much emphasis is placed on the prevention of threats. Threats to the water supply may occur at any stage of the production of water intended for consumption: in the water source, at the stage of treatment and storage, as well as in the water–distribution subsystem. The main causes of undesirable events at the water source indicated based on works [3–11] are:

- adverse weather conditions, for example, floods and droughts,
- events with signs of a major accident and serious failure, the register of which is kept by the Chief Inspectorate for Environmental Protection, for example, the pollution of rivers by various substances,
- disasters caused by oil derivatives in land traffic,
- discharge of untreated sanitary sewage, waste or other hazardous substances to the soil or water,
- leaks of sanitary sewage into the ground from leaking septic tanks,
- drainage of contaminated water used for construction purposes to the ground,
- improper water and wastewater management in industrial plants and facilities associated with animal husbandry,
- slaughterhouses,
- improper agricultural activity, for example, excessive use of plant-protection agents, slurry discharges,
- improperly conducted activities related to the extraction of aggregates,
- corrosion, damage to the construction elements of an intake,
- improper storage of raw water,
- recreational activities on reservoirs, including on post-mining tanks left following aggregate extraction,
- intentional harmful actions of a third party: acts of vandalism or war, and terrorist or cyberterrorist attacks.

We can talk about a threat to safety primarily when there is the contamination of raw water that the conventional treatment process is unable to remove; while there is no possibility of alternative treatment technology being applied. Analysis of the quality of water from the safety of supply should, therefore, extend to contaminants capable of rendering the treatment process ineffective, and thus ensuring that water supplied to the consumer fails to meet regulatory requirements [12,13]. The greatest threat to consumers of water is that associated with biological pollution, so spores and microorganisms should be removed almost completely from water intended for human consumption, while practically, suspensions should be removed completely [14–16].

Turbidity is one of the main parameters determining the utility of water for consumption. In line with binding regulations on the quality of water intended for human consumption, water treatment should aim to achieve a parametric value not exceeding 1.0 NTU in treated water. Water turbidity results from the presence of fine suspensions and colloids of organic or mineral origin. Above all, it should be noted that turbidity applies, not only to the aesthetic properties of water but also to many features that affect health. For example, turbidity is associated with the presence of parasites in the water, affects the effectiveness of disinfection (protecting microorganisms from disinfectants) and lowers the microbiological stability of water in a water-distribution subsystem [17–20].

The water of high turbidity value thus undergoes a process of treatment hampered to a significant degree. While normative turbidity in the 1990s was still at 5 SiO_2/dm^3, research made it clear that harmful microorganisms of various kinds could benefit from turbidity at this level.

Where surface waters are concerned, turbidity and color are the main kinds of pollution capable of being removed by coagulation processes. Turbidity has been chosen as the key parameter of these two. The real color is frequently at a very low level, even as water takes on a specific color, for example being brown in circumstances of heavy rainfall that associate with the presence of suspended matter, that is, turbidity.

The parameter of turbidity should gain use in safety analysis, primarily for surface waters. In the case of groundwater, determining origin is a matter of great importance. If the water contains organic substances in large amounts, the best parameter for risk analysis may be total organic carbon. In turn, if N or P are plentiful, then concentrations of these substances should be considered directly. Iron or manganese may also be used as points of reference in risk analysis. The choice of appropriate parameter for groundwater depends on the specific case, so the best solution will see the technologist knowing the given collective water supply system (CWSS) deciding about it.

The main purpose of the work detailed here has been to analyze the turbidity of surface water as a key parameter determining that water's suitability for human consumption. To that end, this paper proposes a method by which the probability of occurrence of a given level of turbidity can be estimated, this information is regarded as important from the operator of a Water Treatment Plant.

2. Technological safety

A definition of safety in the context of the functioning of a CWSS was that proposed by Rak, who maintained that safety of functioning entails ensuring the continuity of water supply to the consumer, and meeting criteria for system reliability in both quantitative and qualitative terms. Also important are such parameters as a socially acceptable price level per cubic meter of water supplied, with account taken of aspects arising from public-safety requirements, the need to protect the natural aquatic environment, and the standard as regards the quality of life [15].

The measure of loss of safety is risk defined as the probability of occurrence of an undesirable event capable of giving rise to a real threat to the health or life of water consumers [21–28]. Risk analysis relating to a CWSS is most often based on matrix methods, with values for input parameters chosen in a subjective manner by experts.

Here it is the probability of occurrence of water turbidity of a certain value that is analyzed. While the indicator used cannot be identified directly with risk, the estimate of potential losses can be followed by an analysis of the expected loss value $E\ (C \geq C_{limit})$, which is interpreted as a risk. The risk assessment thus includes the following stages [29–35]:

- identification of the hazard,
- assessment of the probability of the hazard arising,
- estimation of the vulnerability to threat,
- consequence analysis.

Technological safety (TS) is defined as the ability of a treatment process to resist internal and external threats. The risk of TS being lost is measured in terms of the risk related to failure (or adverse change) in defined water-quality parameters that may have a negative physicochemical impact on water reaching the consumer. In this aspect, there is a distinguishing of:

- risk relating to direct health threats for consumers (the so-called health risk - *rh*) - involving exceedances in respect of water-quality parameters that pose a direct threat to the health or lives of consumers, with loss of health among the latter ensuing,
- risk relating to threats to technical infrastructure (the so-called technical risk - *rt*) - involving exceedances in respect of water-quality parameters that have a direct negative impact on the technical condition of water-supply infrastructure facilities, but can also indirectly give rise to a deterioration in water quality.

An example of hazards in the latter case may be provided by the corrosive activity of water, damaging water-supply network materials and giving rise to corrosion pits. Ferruginous bacteria then grow, with this, in turn, favoring the formation of biofilms. Where hydraulic conditions are unfavorable, such a sequence of events may result in secondary contamination of water in the water-supply network, with for example a deterioration of organoleptic parameters, but also the presence of pathogenic microorganisms posing a serious threat to human health or life.

In line with safety theory, such a sequence of adverse events is a domino effect, whose initiating event does not impact directly in a loss of safety. It is thus as a result of the sequence of subsequent events that serious consequences may arise [36–40].

3. Research object

The analysis centered on a large town located in southern Poland, which has about 37,000 inhabitants and covers an area of 36.52 km^2. The average 24 h production of treated water there is 5,630.78 m^3/d [41]. The CWSS of the analyzed town is supplied with water using two boundary-wire intakes with a capacity of 17,280 m^3/d, as well underground (three drilled wells of capacity 348 m^3/d). The main source is the boundary-wire intake located on the right bank of the river. In its upper course, the latter flows mostly through forest areas, including the area of a National Park and its surroundings. The area is sparsely populated, so the water level in the upper course of the river is mainly determined by small area pollution and sanitary sewage discharged from small towns located in the valley. In turn, the quality of water below the town under analysis is conditioned mainly by that of the sanitary sewage and industrial effluent discharged. There are several significant industrial plants in the town.

The primary potential threats to the safety of water consumers and the analyzed CWSS are posted by:

- operation of industrial plants located in the vicinity of the water intake,
- a lack of warning and protective stations,
- very limited diversification of the water supply,
- the lack of online monitoring of the water-supply network's hydraulic parameters (including flow rate and pressure), as well as quality parameters, a significant decrease in water consumption in the town, mainly in line with population decline, the rationalization of water consumption and the closure of many places of employment,
- the high or low velocity of water flow increases the risk of secondary water pollution,
- the lack of a water-supply plan in a time of crisis involving alternative intakes.

Collected surface water is treated at the Water Treatment Plant (WTP) using the Actiflo (high-efficiency coagulation) system to reduce both color and turbidity, as well as a set of nine open sand and gravel precipitous filters. Treated water to which chlorine gas has been added goes to the initial tank of capacity 5,000 m^3. Should the turbidity in raw water emerge as too high, or should an emergency arise, such tanks constitute a reserve of water for about 22 h. Initial tanks also ensure the time necessary for water to make contact with chlorine. Water is pumped to the network using four III^o pumps controlled by the constant pressure algorithm. During normal operation, one pump is operating in the exchange system every 24 h, while the remaining pumps constitute a reserve. Based on the WTP technological scheme made available by the water supply company and operating since modernization work was completed in 2009, the reliability scheme for the analyzed WTP is as presented in Fig. 1 [41].

In line with turbidity being one of the main parameters determining surface water's utility for consumption, turbidity measurements for the analysed WSS are made several times during the water-treatment process. These involve:

- measurement of the turbidity of collected water,
- measurement of the turbidity of water that has passed through settling tanks,
- measurement of the turbidity of water that has passed through the Actiflo blocks,
- measurement of the turbidity of water pumped into the town (having come through fast filters).

4. Research methodology

Information on the turbidity of raw water was obtained from the water-supply company. As data from the years 2010–2015 were collected, the research refers to the period following the WTP's modernization offending in late 2009. The modernization mainly entailed the installation of the aforementioned Actiflo system, modernization of the fast filters, construction of a new 5,000 m^3 clean water tank and process automation. Raw-water turbidity measurements were usually made twice a day, thus generating significant research material allowing the likelihood of turbidity of a certain value occurring to be determined. Turbidity of more than 1,000 NTU may result in an intake being closed, as well as in a need for water accumulated in clean water reservoirs and network tanks to be made use of. The technology of water treatment at the WTP is based on the Actiflo system, and a set of nine rapid filters allows for turbidity removal even above 1,000 NTU. However, the intake is closed in periods of increased turbidity, due to the need to use an increased amount of coagulant, with the attendant raised operating costs and increased dosing with chemicals that denote.

The research material comprised 4,369 turbidity measurements for raw water made during the 6 years covered by the analysis. Small gaps in the database result from a lack of certain 2010 turbidity measurements coinciding with weekends or holidays. The data were processed appropriately, with key statistical measures for turbidity determined for each month covered by the analysis. This made it possible to encapsulate and present any seasonality to turbidity, as well as to indicate the periods in a given year characterized by the greatest turbidity of water.

In cooperation with the water-supply company, it was assumed that the reaching of 1,000 NTU of river water turbidity should be taken as requiring consideration of whether exploitation ought to cease until the situation normalizes. As this value is not a threshold regulated by law, a different one might be adopted, depending on the degree of advancement of the technological process, as well as the financial means available to the water-supply company.

Currently, thanks to the proper use of EU funding, the water company in question has a treatment technology allowing for the removal of significant turbidity, up to several thousand NTU. Equally, the higher the water turbidity, the greater the costs of water treatment.

The stage in question also allowed for determinations of changes in the turbidity of raw water in recent months and years. An attempt was also made to determine the "a posteriori" probability of occurrence of turbidity of a certain value, based on Bayes's Theorem.

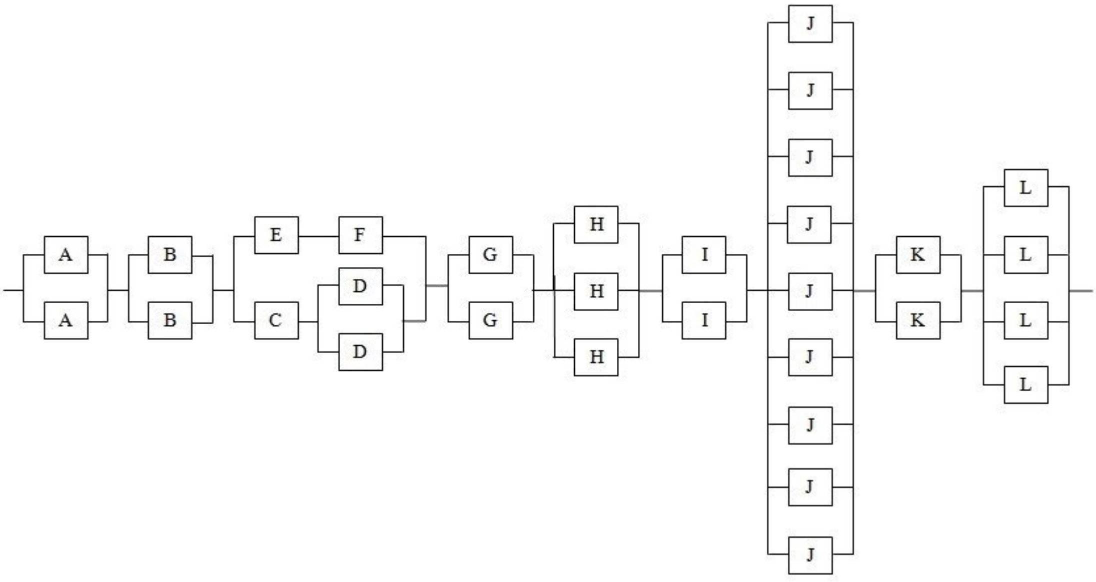

Fig. 1. WTP reliability scheme. Symbols mean *A* - inlet windows, *B* - grits, *C* - collecting wells, *D* - I^o pumps, *E* - collective wells (reserves), *F* - I^o pumps (reserves), *G* - initial settling tanks, *H* - II^o pumps, *I* - Actiflo blocks, *J* - fast filters, *K* - clean water tanks, *L* - III^o pumps.

In the work, the Bayesian theorem was used to determine the probability of turbidity at a certain value, allowing for the updating and correction of strong beliefs based on scientific evidence in the light of new "a posteriori" evidence [42]:

$$P(A \mid B) = \frac{P(B \mid A) \times P(A)}{P(B)} \tag{1}$$

where $P(A)$ is the "a priori" probability of occurrence of event A, $P(B)$ the "a priori" probability of occurrence of event B, $P(A/B)$ the conditional probability of occurrence of event A on the condition that event B occurs (it is also called the probability "a posteriori" as it comes from or depends on the value of event B). $P(B/A)$ is in turn the conditional probability of occurrence of event B provided that event A occurs.

The "a priori" probability means the initial probability value prior to additional information originating from experience being obtained. The "a posteriori" probability means the probability value obtained following the use of additional information obtained later on the basis of experience.

5. Test results

5.1. Seasonality to the turbidity of raw water

The results of turbidity measurements made in the laboratory located at the Water Treatment Plant were analyzed. The information was obtained from the water-supply company. The variability characterizing the turbidity of water taken over the analyzed period is as shown in Fig. 2.

The results of the analysis for individual months and years covered by the analysis were also shown on box charts (Fig. 3), which present basic statistical characteristics. This stage allowed changes in the turbidity of raw water over the most recent months and years to be determined.

The analysis revealed a marked seasonality to the turbidity of the water in use. However, in the vast majority of cases, turbidity in exceeds of 15 NTU was not noted. Maximum values were noted in May, June, and July, probably in line with intense rainfall occurring then. Over the analyzed period, the highest turbidity values of all were noted in 2010 (a year in which heavy rain and flooding affected the town understudy). A large number of extreme values offer a noteworthy reflection of the incidental nature of the phenomenon under study. In individual years, increased turbidity values also appeared at the end of February, in March or at the beginning of April, in the course of events that readily be related to thaws taking place. To provide for a detailed analysis of seasonal fluctuations in turbidity, a seasonality index Si was used, in line with a dependent relationship as follows [43]:

$$S_i = \frac{\overline{y}_i \times d}{\sum_{i=1}^{d_j} \overline{y}_i} \times 100 \tag{2}$$

where Si is the seasonality index for the i-th sub-period, yi is the arithmetic mean for turbidity in one-name sub-periods (months) in 2010–2015, and d_j is the number of one-name sub-periods (number of months).

Calculation example for March:

Total turbidity exceedances (>100 NTU): 10 + 6 + 9 + 3 + 3 + 1 = 32.

Arithmetic average of turbidity exceedances in identical sub-periods (months):

$$\overline{y}_i = \frac{32}{6} = 5.33 \tag{3}$$

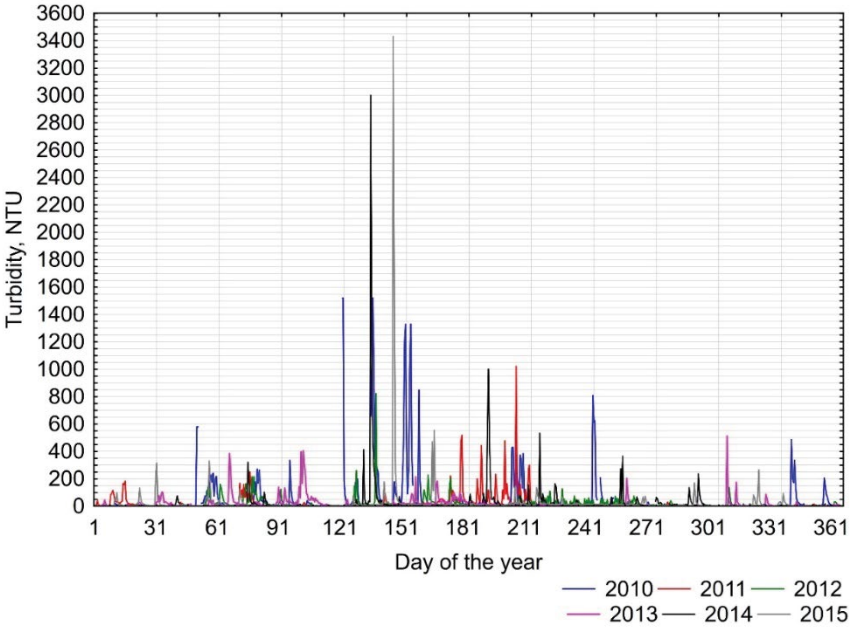

Fig. 2. Variability to the turbidity of water taken in the years 2010–2015 by day of the year.

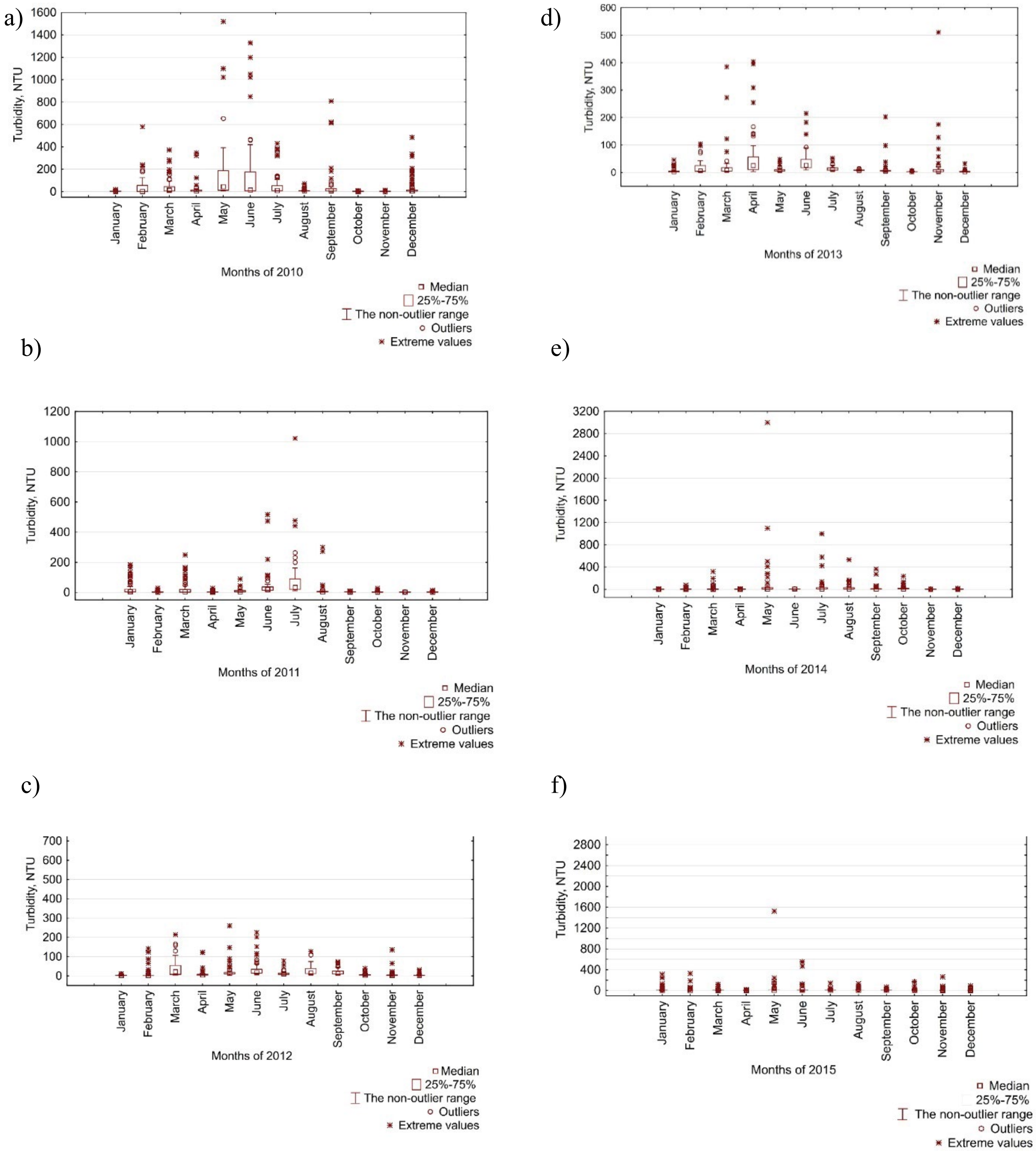

Fig. 3. Turbidity of raw water in the years 2010–2015 (a)–(f).

We divide the number of exceedances in an analyzed period (equal to 32) by the number of months analyzed, that is, March from 2010 to 2015 (equals 6).

We calculate the seasonality index for the *i*-th sub-period using:

$$S_i = \frac{6 \cdot 12}{1.67 + 2 + 5.33 + 2 + 6 + 5.17 + 4.83 + 1.5 + 1.5 + 0.67 + 0.83 + 2} \times 100 = 191.04\% \quad (4)$$

We divide the product of the arithmetic mean of the number of turbidity exceedances in March and the number of months in a year by the sum of the arithmetic mean of turbidity exceedances in individual months (from January to December).

The seasonal index *S*i determines the amount of a change in the average monthly number of turbidity exceedances, $\bar{y} = \frac{201}{72} = 2.79$ (100%). Since turbidity ≥1,000 NTU was only recorded a few times during the study period, the analysis covered all cases of turbidity above 100 NTU, given the way that [44] suggests problems with water treatment being caused by this level upwards.

The results are compiled in Table 1 and also shown in Fig. 4.

The number of turbidity occurrences over 100 NTU was found to be greater than the average monthly number of turbidity exceedances in four months, that is, March (by 91.04%), May (by 114.93% - the highest value), June (by 85.07%) and July (by 73.13%).

Clean water tanks and network tanks allow for closure of intake for about 22 h, without any need to limit the supply of water to consumers if the tanks are 100% full. The river in the analyzed town is characterized by very diverse turbidity. However, across the analyzed period, the longest spell of river water turbidity exceeding 1,000 NTU lasted just 1 d (the Actiflo system can remove turbidity at 100 NTU). On this basis, both as the work and information from the water company confirmed no need for water supply to the town to be suspended on account of poor water quality, at any time in the years 2010–2015.

5.2. Probability of a certain value of turbidity occurring

It is very important for the WTP operator to have information on the probability that turbidity at a certain level will occur. On the basis of acquired turbidity data for water taken, it was possible to determine such a probability of occurrence of turbidity of a certain value (Table 2).

The "a priori" probability of turbidity at the level <0–264) is as high as 0.983. However, these most common occurrences reflect turbidity not posing a threat to the continuity of the water treatment process. In contrast, the likelihood of there being turbidity equal to 1,056 NTU or higher is 0.002, though this probability can be modified in line with the knowledge possessed. The results obtained in the course of water-quality analysis provide no certainty as to the correctness of tests performed, as measurement is burdened by error resulting from the method in which test samples are taken, the different states of suspended particles in water, the presence of color, the presence of air bubbles and, above all, the experience and diligence of the laboratory. Given the uncertainty of measurement, a 0.1% probability of a measurement error being made was assumed. Event-B is actual value for the turbidity of raw water.

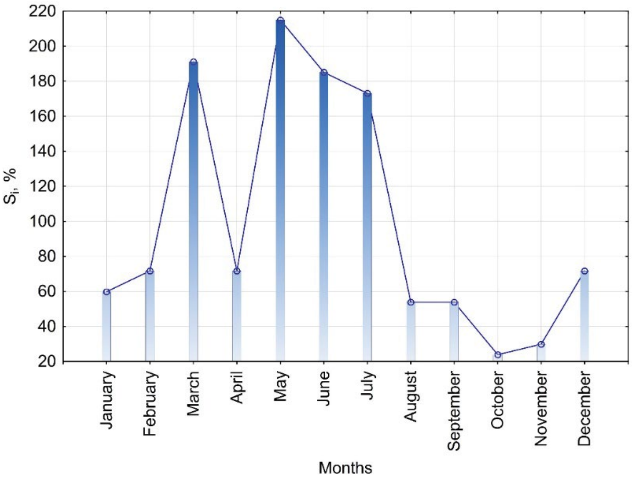

Fig. 4. Relative seasonal variations in the occurrence of turbidity above 100 NTU in the 2010–2015 period.

The course of action is as follows. It is assumed that the obtained turbidity result is 300 NTU, while analysis of water consumed provides new information for inclusion in further analyzis. The a posteriori probability is given by formula (3–5).

$$P(A_1|B)=\frac{0.983\times 0.0005}{0.983\times 0.0005+0.011\times 0.999+0.002\times 0.0005}=0.043$$

– the probability "a posteriori" that the tested value of 300 NTU is in the range <0–264) (5)

$$P(A_2|B)=\frac{0.011\times 0.999}{0.983\times 0.0005+0.011\times 0.999+0.002\times 0.0005}=0.957–$$

the probability "a posteriori" that the tested value of 300 NTU is in the range <264–528) (6)

$$P(A_3|B)=\frac{0.002\times 0.0005}{0.983\times 0.0005+0.011\times 0.999+0.002\times 0.0005}=0 \quad –$$

the probability "a posteriori" that the tested value of 300 NTU is in the range <528–792) (7)

The probabilities were determined to assume a measurement error of 0.1%.

The general form of the formula is:

$$P(A_i|B)=\frac{P(A_i)\times P(B/A_i)}{\sum P(A_i)\times P(B/A_i)} \tag{8}$$

where $P(A_i)$ is the probability of occurrence of specific water turbidity (within a given range), and $P(B/A_i)$ is the probability that the measured turbidity corresponds to the result of the given range (confidence level).

The acquisition of new information on actual turbidity affects the probability of occurrence of a specific turbidity value. The "a posteriori" probability that the turbidity is <0–264) is $P(A1|B) = 0.043$. The probability that the measured turbidity is actually <264–528) is $P(A2|B) = 0.957$. The analysis conducted indicates that the result of just a single turbidity test should not be relied upon.

The a priori probability relates to classical probability. It is obtained by dividing the obtained number of results in a given turbidity range by the number of all measurements carried out. In this case, given the lack of absolute certainty about the results of the study, the a posteriori probability is determined by reference to the level of confidence associated with the result. In line with Bayes's theorem, a determination is made as to the probability that the tested value of 300 NTU belongs to the range <264–528) NTU, and which is that it is higher or lower.

The major difference between the results for "a priori" and "a posterior" probabilities results from the fact that they relate to two different things. The "a priori" probability

Table 1
Determination of the seasonal index for turbidity greater than 100 NTU in the years 2010–2015

Months	Number of turbidity samples >100 NTU						Total	$\bar{y}_i$	S_i
	2010	2011	2012	2013	2014	2015			
January	0	7	0	0	0	3	10	1.67	59.70
February	7	0	2	1	0	2	12	2.00	71.64
March	10	6	9	3	3	1	32	5.33	191.04
April	3	0	1	8	0	0	12	2.00	71.64
May	21	0	3	0	7	5	36	6.00	214.93
June	14	5	5	3	0	4	31	5.17	185.07
July	11	13	0	0	4	1	29	4.83	173.13
August	0	2	2	0	4	1	9	1.50	53.73
September	6	0	0	1	2	0	9	1.50	53.73
October	0	0	0	0	3	1	4	0.67	23.88
November	0	0	1	3	0	1	5	0.83	29.85
December	12	0	0	0	0	0	12	2.00	71.64
Total of samples	84	33	23	19	23	19	201	33.5	

was the basis upon which to determine the probability that the turbidity value tested falls within a certain range (based on a certain confidence level).

6. Conclusions

High turbidity in raw water causes great difficulties for water treatment. It is associated with the presence of microorganisms and acts to shield the latter from the impacts of disinfectants. If water suitable for consumption is to be assured, spores and microorganisms should be almost entirely removed from the water, which is to say that suspension should be practically absent by the time treatment is complete. The turbidity parameter is very important because it offers much information regarding the likely impact of water on human health.

Table 2
Probability of occurrence of specific turbidity in the examined river in the years 2010–2015

Class	Range of turbidity NTU	Number of samples	Probability "a priori" $P(A\mathrm{i})$
A_1	<0–264)	4,296	0.983
A_2	<264–528)	48	0.011
A_3	<528–792)	7	0.002
A_4	<792–1,056)	8	0.002
A_5	<1,056–1,320)	3	0.001
A_6	<1,320–1,584)	5	0.001
A_7	<1,584–1,848)	0	0
A_8	<1,848–2,112)	0	0
A_9	<2,112–2,376)	0	0
A_{10}	<2,376–2,640)	0	0
A_{11}	<2,640–204)	0	0
A_{12}	<2,904–368)	1	0
A_{13}	<368–3,432)	1	0

The analysis presented here considers the impact on the safety of supply exerted by turbidity in surface water used by a town in southern Poland. In the event, there was no time during the analyzed period in which it proved necessary to suspend the above town's water supply on account of inadequate quality of water taken in. In periods of the greatest turbidity, water intake was closed off for several hours, with use then being made of water collected in tanks. The effectiveness of the Actiflo system installed in 2009 should, therefore, be assessed positively, given that it has worked very well in treating water of rapidly changing turbidity that periodically reaches several thousand NTU, if in cooperation with a clean water reservoir.

The highest turbidity values were recorded in May, June, and July, probably in connection with the intense rainfall occurring during this period. Individual years also saw increased turbidity values at the end of February, in March or at the beginning of April, with the reason, in this case, being the spring thaw.

The method developed to determine the probability of occurrence of a specific value for water turbidity using the Bayesian theorem should be used to analyze the "a posteriori" probability of occurrence of certain values for parameters determining the utility of water for consumption.

References

[1] WHO, Water Safety Plan Manual: Step-by-Step Risk Management for Drinking-Water Suppliers, World Health Organization, Geneva, 2009.
[2] WHO, Guidelines for Drinking-Water Quality, 4th ed., World Health Organization, Geneva, 2011.
[3] B. Tchórzewska-Cieślak, Methods of Analysis and Assessment of Failure Risk of the Water Distribution Subsystem, Rzeszów University of Technology Publishing House, Rzeszów, 2011 (in Polish).
[4] P. Marcinowski, M. Wojtkowska, G. Sinicyn, Surface water monitoring in the area of the Zelazny Most waste disposal, Przem. Chem., 87 (2008) 512–519.
[5] A. Nowacka, M. Wlodarczyk-Makula, B. Tchorzewska-Cieslak, J. Rak, The ability to remove the priority PAHs from water

during coagulation process including risk assessment, Desal. Wat. Treat., 57 (2016) 1297–1309.

[6] D. Kowalski, B. Kowalska, M. Kwietniewski, Monitoring of water distribution system effectiveness using fractal geometry, Bull. Pol. Acad. Sci., Chem., 63 (2015) 155–161.

[7] I. Zimoch, Pressure control as part of risk management for a water-pipe network in service, Ochr. Sr., 34 (2012) 57–62.

[8] J. Krolikowska, A. Krolikowski, Fees for a storm water discharge - needs and possibilities, Rocz. Ochr. Srod., 15 (2013) 1143–1152.

[9] J. Krolikowska, B. Debowska, A. Krolikowski, An Evaluation of Potential Losses Associated With the Loss of Vacuum Sewerage System Reliability, D. Pawlowski, Pawlowski, eds., Environmental Engineering IV, Taylor & Francis Group, London, 2013, pp. 51–57.

[10] D. Szpak, B. Tchórzewska-Cieślak, Modelling of failure rate of water supply network using the Bayes theorem, E3S Web. Conf., 44 (2018) 1–6.

[11] J. Rak, K. Boryczko, Assessment of water supply diversification using the Pielou index, Environ. Sci., (2017) 53–58, doi: 10.1201/9781315281971-8.

[12] Council Directive 98/83/EC of 3 November 1998 on the Quality of Water Intended for Human Consumption, with Its Latest Amendments Including Commission Directive (EU) 2015/1787 of 6 October 2015, Official Journal of the European Union, 7 October 2015.

[13] M. Smol, M. Wlodarczyk-Makula, B. Skowron-Grabowska, PAHs removal from municipal landfill leachate using an integrated membrane system in aspect of legal regulations, Desal. Wat. Treat., 69 (2017) 335–343.

[14] J.R. Rak, B. Tchorzewska-Cieslak, M. Wlodarczyk-Makula, J. Rak, Safety analysis of the wastewater treatment process in the field of organic pollutants including PAHs, Desal. Wat. Treat., 72 (2017) 146–155.

[15] J.R. Rak, Some aspects of risk management in waterworks, Ochr. Sr., (2007) 61–64.

[16] V. Ondrejka Harbulakova, A. Estokova, M. Kovalcikova, Correlation analysis between different types of corrosion of concrete containing sulfate resisting cement, Environments, 44 (2017) 4030044.

[17] A. Chełmicka, L. Kiedryńska, Estimation of relation between turbidity units, Sci. Rev. Eng. Environ. Sci., 31 (2005) 195–200.

[18] B. Olearczyk-Siwik, The problem of excessive raw water turbidity by example of the Czaniec reservoir, Min. Environ., 9 (2010) 6374.

[19] J. Rak, B. Tchórzewska-Cieślak, Review of matrix methods for risk assessment in water supply system, J. Konbin, 1 (2006) 67–76.

[20] I. Jiménez-Pardo, L.G.J. Van der Ven, R.A.T.M. Van Benthem, G. De With, A.C.C. Esteves, Hydrophilic self-replenishing coatings with long-term water stability for anti-fouling applications, Coatings, 8 (2018) 184.

[21] B. Tchorzewska-Cieslak, Estimating the acceptance of bearing the cost of the risks associated with the management of water supply system, Ochr. Srod., 29 (2007) 69–72 (in Polish).

[22] B. Tchorzewska-Cieslak, Risk management in water safety plans, Ochr. Srod., 31 (2009) 57–60.

[23] I. Zimoch, E. Lobos, Comprehensive interpretation of safety of wide water supply systems, Environ. Prot. Eng., 38 (2012) 107–117.

[24] Q. Shuang, Y.S. Liu, Y.Z. Tang, J. Liu, K. Shuang, System reliability evaluation in water distribution networks with the impact of valves experiencing cascading failures, Water, 9 (2017) 413.

[25] S. Kaplan, B.J. Garrick, On the quantitative definition of risk, Risk Anal., 1 (1981) 11–27.

[26] T. Aven, Conceptual framework for risk assessment and risk management, J. Pol. Saf. Reliab. Assoc., 1 (2010) 15–27.

[27] T. Aven, Risk Analysis: Assessing Uncertainties Beyond Expected Values and Probabilities, John Wiley & Sons, Chichester, 2008.

[28] I. Piegdoń, B. Tchórzewska-Cieślak, D. Szpak, The Use of Geographical Information System in the Analysis of Risk of Failure of Water Supply Network, M. Pawlowska, L. Pawlowski, Environmental Engineering V, Taylor & Francis Group, 2017, pp. 7–14.

[29] B. Tchorzewska-Cieslak, A fuzzy model for failure risk in water-pipe networks analysis, Ochr. Sr., 33 (2011) 35–40.

[30] B. Tchorzewska-Cieslak, Bayesian model of urban water safety management, Global Nest J., 16 (2014) 667–675.

[31] S. Lee, S. Oak, D. Jung, H. Jun, Development of failure cause–impact–duration (CID) plots for water supply and distribution system management, Water, 11 (2019) 1719.

[32] I. Zimoch, Computer simulation as a tool assisting in the operation of a water supply system, Ochr. Srod., 3 (2008) 31–35.

[33] J. Rak, A study of the qualitative methods for risk assessment in water supply systems, Environ. Prot. Eng., 29 (2003) 123–133.

[34] M. Eid, Modelling sequential events for risk, safety and maintenance assessments, J. Pol. Saf. Reliab. Assoc., 1 (2010) 83–87.

[35] O. Pozos-Estrada, A. Sanchez-Huerta, J.A. Brena-Naranjo, A. Pedrozo-Acuna, Failure analysis of a water supply pumping pipeline system, Water, 8 (2016) 395.

[36] P.M. Huck, B.K. Siembida-Loesch, M.M. Sozanski, Biological Filtration for Diverse Applications: Towards the Development of a Unified Conceptual Design Approach, KWR Water Cycle Research Institute, Nieuwegein, 2014.

[37] B. Kaźmierczak, M. Wdowikowski, Maximum rainfall model based on archival pluviographic records – case study for Legnica (Poland), Period Polytech. Civ., 60 (2016) 305–312.

[38] M. Kutyłowska, Comparison of two types of artificial neural networks for predicting failure frequency of water conduits, Period Polytech. Civ., 61 (2017) 1–6.

[39] J. Zamorska, D. Papciak, Activity of nitrifying biofilm in the process of water treatment in diatomite bed, Environ. Prot. Eng., 34 (2008) 37–52.

[40] M. Zielina, W. Dabrowski, T. Lang, Assessing the risk of corrosion of asbestos-cement pipes in Krakow's water supply network, Environ. Prot. Eng., 33 (2007) 17–26.

[41] D. Szpak, B. Tchórzewska-Cieślak, Analysis and assessment of water treatment plant reliability, J. Konbin, 41 (2017) 2138.

[42] J.M. Bernardo, A.F.M. Smith, Bayesian Theory, Wiley, Chichester, 1993.

[43] M. Sobczyk, Statistics: Theoretical and Practical Aspects, Maria Curie-Sklodowska University Publisher, Lublin, 2006.

[44] J. Pawełek, Use of Water Supply to Secure Water Intakes from Rivers and Mountain Streams in Conditions of Elevated Turbidity and Suspended Matter, Publishing House of the University of Agriculture in Krakow, Krakow, 1996 (in Polish).