Application of risk-based approach in design of water supply systems

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Abstract. The formation of organochlorine compounds in drinking water in the water supply system chlorination process was studied. The dynamic pattern of chloroform concentration in drinking water in a water treatment facility over a year is provided. Cancer health risk for the population of using drinking water is calculated. A greater speed of organochlorine compound formation in comparison with the rising concentration of residual chlorine associated with a bigger dose of chlorine agent was documented. The influence of such factors as pH medium, permanganate oxidizability, chlorine absorbing capacity, temperature and residual chlorine concentration on the concentration of chloroform in drinking water was experimentally established. A neural network model that predicts the chloroform concentration in drinking chlorine treated water was used. The chlorine agent dosage control organization chart was proposed on the basis of fuzzy logic that can be used in design of water-supply systems taking into account the health risks for the population.

1. Introduction
Chlorine treatment is one of the methods of water disinfection at water treatment facilities both in Russia and abroad [1-3]. The consequence of introducing a chlorine agent is the formation of organochlorine compounds. This can create a cancer health risk for the population when taking such a dose, this is why it is essential to find the optimal dose of chlorine agent that can protect from communicable diseases while forming minimum cancer inducing substances [4].

In order to solve this problem the researchers have made attempts to change the technological disinfection process by partially substituting chlorine treatment with ozone one [5], eliminating chlorine treatment subproduct organoprecursors with nanofiltration membranes [6-9], carrying out additional water treatment after secondary chlorine treatment with UV exposure [10]. Chemical methods for the elimination of coagulation water treatment precursors after initial chlorine treatment and bigger dose of a coagulant [11] and of chlorine-substituted organic water polluters after their formation with activated charcoal [12] are used.

The task of ensuring a lower risk of excessive or insufficient chlorine treatment can be solved by designing a smart, automated, adaptive, dynamically developing system for managing water treatment process parameters that is built using fuzzy logic and allowing introducing algorithms into manual processes on the basis of professional knowledge and skills [13-19]. It is essential to add a control parameter in this system that is associated with risk assessment as it is done in other technologies [20].
Thus, the goal of the study was to improve the chlorine agent dosage system at water treatment facilities on the basis of a risk-oriented approach with a view to lower cancer risks from drinking water.

2. Methodology
In order to identify the impact of various factors in treatment process and of water quality on the formation of organochlorine compounds an experiment was conducted. Such parameters as pH medium, permanganate oxidizability, chlorine absorbing capacity, temperature were changed, and the chloroform concentration was checked. The ranges of parameter change and margin error in their calculation are provided in Table 1.

| Factors                        | Ranges     | Margin error |
|--------------------------------|------------|--------------|
| pH medium, units pH            | 7.5 – 8.5  | 0.2          |
| Temperature, °C                | 2 – 28     | 0.1          |
| Chlorine absorbing capacity, mg/dm³ | 1.8 – 2.2 | 10 %         |
| Permanganate oxidizability, mg/dm³ | 4.4 – 7.6 | 10 %         |

Temperature and pH medium was measured with relevant equipment. Permanganate oxidizability and chlorine absorbing capacity were identified analytically. Chloroform concentration was established employing the chromatograph method.

With a view to identify the impact of this chlorine dose and residual chlorine, the dynamics of these parameters was tracked over a year as well as those of chloroform. The chlorine dose is the function of the used chlorine dosage to the volume of chlorine treated water. This research was conducted on the basis of hourly updated data at a water treatment facility. Moreover, a simulation experiment was carried out where the chlorine dose was artificially increased by three times.

Neural network simulation was used to build a forecast model to predict the chloroform concentration in drinking water based on water quality parameters and chlorine treatment process. Feed-forward backprop network was used with direct signal transfer and back propagation of error with 50 neurons. The number of training examples was about 6000. Neural network simulation allows chloroform concentration control in real time which is impossible if the chromatograph method is used.

Cancer risk factor in chlorine agent dosage control in water supply systems was proposed by the introduction of fuzzy logic apparatus. A linguistic variable was used as one of the control parameters, namely chloroform concentration. Membership functions of this variable were chosen based on the acceptability of the cancer risk for various population groups. Three subsets with risk ranges were identified: less $10^{-6}$, $10^{-6} – 10^{-5}$, $10^{-5} – 10^{-4}$. The values higher than $10^{-4}$ were not considered as they lie beyond the acceptable risk for the population. The risk lower than $10^{-6}$ is considered negligible. The risk in the range of $10^{-6} – 10^{-4}$is subject to continual monitoring. The general dosage control chart at water supply facilities providing for possible cancer risk is shown in Figure 1.

Neural network simulation and imitation dosage control model were implemented in MATLAB software environment using Neural Networks Toolbox and Fuzzy Logic Toolbox.

3. Results
The analysis of the function of chloroform concentration and pH medium, permanganate oxidizability, chlorine absorbing capacity, temperature showed the non-linear nature of these functions that is shown in Figures 2-5. The greatest chloroform concentration was obtained when chlorine absorbing capacity
was changed and corresponded to the cancer health risk for the population in case of water consumption of $5.14 \times 10^{-6}$.

**Figure 1.** General control chart for chlorine treatment process on the basis of fuzzy logic.

**Figure 2.** Function of chloroform concentration and temperature.

**Figure 3.** Function of chloroform concentration and permanganate oxidizability.

**Figure 4.** Function of chloroform concentration and pH medium.

**Figure 5.** Function of chloroform concentration and chlorine absorbing capacity.
Chloroform concentration dynamics over a year at a water treatment facility is shown in Figure 6. The dynamics analysis showed that the concentration varied from 0.0012 to 0.018 mg/dm$^3$ and about 70% of the total measurements over a year was higher than the chloroform concentration with the cancer risk being near the upper limit of acceptable risk ($10^{-6}$) and is subject to constant monitoring. The surges in the dynamics could not be explained uniquely by the chlorine dosage and the concentration of residual chlorine in the water.

Figure 6. Chloroform concentration dynamics over a year.

The conducted simulation experiment in artificial chlorine dosage increase by three times showed that the speed of residual chlorine growth is less than that of organochlorine compound concentration growth under the same conditions. The results are provided in Table 2. If the dose of chlorine agent is twice its dose, then the total per-oral risk is twice over the health risk norm for the population.

| Chlorine agent dose (mg/dm$^3$) | Residual chlorine concentration, (mg/dm$^3$) | Total per-oral risk     |
|----------------------------------|---------------------------------------------|-------------------------|
| 0.7                              | 0.9                                         | 0.000001189             |
| 1.0                              | 1.2                                         | 0.000004896             |
| 1.3                              | 1.7                                         | 0.000015225             |
| 1.7                              | 2.1                                         | 0.000022465             |
| 2.0                              | 2.4                                         | 0.000176807             |
| 3.0                              | 2.9                                         | 0.000251134             |

The built neural network model that predicts the chloroform concentration on the basis of pH medium, permanganate oxidizability, chlorine absorbing capacity, temperature and residual chlorine concentration was tested using the real sample of 500 items. The correlation coefficient between the experimental values and the values calculated based on the model was 0.88 that proves the relevance of the developed model.

The graphic representation of fuzzy logic rules of the imitation dosage control model with Fuzzy Logic Toolbox is shown in Figure 7.
Figure 7. Grafic representation of fuzzy conclusion rules.

When the model was tested, the neural fuzzy conclusion in the form of a linguistic variable "Chlorine dose coefficient" that manages the dosage on the basis of residual chlorine concentration, the speed of its change and chloroform concentration. The dosage in the existing systems is done on the basis of chlorine absorbing capacity and residual chlorine concentration. It was established that the system functions properly in accordance with the preset fuzzy rule system.

4. Conclusion

Thus the research of factors affecting the formation of organochlorine compounds allowed to develop a neural network to predict the chloroform concentration in chlorine-treated drinking water. The model can predict in real time such parameters as pH medium, permanganate oxidizability, chlorine absorbing capacity, temperature and residual chlorine concentration.

The chlorine agent dosage control organization chart was proposed on the basis of fuzzy logic that can be used in design of water-supply systems taking into account the health risks for the population. This result has been achieved thanks to the introduction of a control parameter into the dosage system, namely the concentration of chloroform in its relation to the level of cancer risk. Tracking the speed and concentration of residual chlorine allowed to react faster to changes in water quality. These factors all together allowed to create a more flexible control system for chlorine agent dosage and significantly diminish the risk of excessive chlorine treatment that leads to the formation of cancer inducing substances in water.

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Acknowledgments
The reported study was funded by RFBR according to the research project No 18-35-00489.