Artículo de investigación

Approaches to risk assessment and selection of water treatment technologies to provide consumers with quality drinking water

Подходы к оценке рисков и выбору технологий водоподготовки для обеспечения потребителей качественной питьевой водой

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Abstract

The processes of organizing centralized drinking water supply for the population are based on the requirements of sanitary legislation and technical regulation, depending on the quality of available water sources on the applied technological solutions in the field of water treatment, as well as on the infrastructure of water supply processes. At the same time, the quality of drinking water from centralized systems is one of the most important criteria for the operation of enterprises in the city water supply and sewage system. The inconsistency of the quality of drinking water with centralized water supply, regularly noted in the reports of Federal Agency for Consumer Protection (Rospotrebnadzor), indicates problems of ensuring the safety of the population, and, on the other hand, incurs additional financial costs for the water supply company. It should be noted that the preservation and assessment of the quality potential of water supply sources, which under the influence of anthropogenic factors is under constant threat of degradation, is also an important factor in influencing the organization of centralized drinking water supply from the point of view of standardizing technological and infrastructural solutions. Legislative requirements in the field of drinking water quality make it extremely difficult to fulfill obligations to supply the population with drinking water of the required quality. It should be noted that the existing regulatory documents regulating the methodology of sanitary - hygienic assessment of water quality do not fully take into account the modern technological capabilities of the facilities

Аннотация

Процессы организации централизованного питьевого водоснабжения населения находятся, исходя из требований санитарного законодательства и технического регулирования, в определяющей зависимости от качества имеющихся водных источников, от применяемых технологических решений в области водоподготовки, а также от инфраструктуры процессов водоснабжения. Вместе с тем, именно качество питьевой воды централизованных систем является одним из важнейших критериев работы предприятий городского водопроводно-канализационного хозяйства. Факты несоответствия качества питьевой воды централизованного водоснабжения, регулярно отмечаемые в докладах Роспотребнадзора, с одной стороны свидетельствуют о проблемах обеспечения безопасности населения, а с другой стороны, ложатся дополнительным финансовым бременем на предприятие водоснабжения. Следует отметить, что сохранение и оценка потенциала качества источников водоснабжения, которые под действием антропогенных факторов находится под постоянной угрозой деградации, также является важнейшим фактором влияния на организацию централизованного питьевого водоснабжения с точки зрения стандартизации технологических и инфраструктурных решений. Законодательные требования в области качества питьевой воды делают чрезвычайно затруднительным выполнение обязательств

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for the preparation and transportation of drinking water, including change in emissions of pollutants caused by anthropogenic or natural causes.

Despite the significant scientific and methodological amount of data regarding the formation of requirements for centralized drinking water supply, the issues of ensuring the required water quality remain insufficiently studied. There is a need for interconnection of standardization of approaches to the selection of technological solutions and equipment, the formation and management of infrastructure facilities, evaluation of the effectiveness of design and operational components of water supply systems, sufficient and necessary levels of sanitary and technological safety, based including on economic efficiency and enterprise capabilities. The principles of designing new infrastructure facilities and centralized drinking water supply facilities and reconstruction of existing ones should be based on the proposed integrated life cycle cost methodology, which allows optimizing production and investment costs of urban facilities.

Issues of providing high-quality drinking water through centralized water supply systems are resolved separately from the standpoint of hygiene requirements, technological and organizational solutions. This article proposes approaches that choose an effective water treatment technology, taking into account the assessment of health risks, positioning the technical factors of the water supply system and the economic assessment of the technology, taking into account the above points.

Key words: Water treatment, drinking water, risk assessment, life cycle cost

по снабжению населения питьевой водой требуемого качества. Отметим, что существующие нормативные документы, регламентирующие методику санитарно - гигиенической оценки качества воды, не в полной мере учитывают современные технологические возможности объектов подготовки и транспортировки питьевой воды, в т.ч. изменение эмиссий загрязняющих веществ, вызванное антропогенными либо естественными причинами.

Несмотря на имеющийся значительный научный и методический объем данных в части формирования требований к централизованному питьевому водоснабжению, остаются недостаточно изученными вопросы обеспечения требуемого качества воды. Необходима взаимосвязь стандартизации подходов к выбору технологических решений и оборудования, формирования и управления объектами инфраструктуры, оценки эффективности проектных и эксплуатационных составляющих систем водоснабжения, достаточного и необходимого уровней санитарной и технологической безопасности, основанная в т.ч. на экономической эффективности и возможностях предприятия. Принципы проектирования новых объектов инфраструктуры и сооружений централизованного питьевого водоснабжения и реконструкция действующих должны основываться на предложенной интегральной методике затрат жизненного цикла, которая позволяет оптимизировать производственные и инвестиционные затраты объектов городского хозяйства.

Вопросы обеспечения качественной питьевой водой посредством систем централизованного водоснабжения решаются отдельно с позиций гигиенических требований, технологических и организационных решений. В настоящей статье предложены подходы, позволяющие выбрать эффективную технологию водоподготовки, с учетом оценки рисков для здоровья, позиционирования технических факторов системы водоснабжения и экономической оценке технологии, учитывающей вышеперечисленные моменты.

Ключевые слова: водоподготовка, питьевая вода, оценка рисков, стоимость жизненного цикла

Introduction

Water supply and providing consumers with quality drinking water are determined by the need to solve several interrelated tasks, which include:

- Definition and quality assurance of the water supply source of a settlement or enterprise
- Selection of water treatment technologies taking into account the quality of the water source and regional characteristics
- Ensuring the quality of water supplied to subscribers in accordance with legal requirements
- Economic feasibility of applying selected technical solutions

At present, the Federal project "Clean Water" (National project "Ecology") has been launched in the Russian Federation, according to which it is necessary to improve the quality of drinking water of centralized water supply systems. We believe that it is necessary to move away from the technological approach and consider issues of improving the quality of water treatment through the interconnection of hygienic, technological and organizational aspects inherent in centralized drinking water supply systems

Methods

The main requirement for measuring water quality is that the levels do not exceed the standard by more than the value of the permissible error of the determination method (see article 23, paragraph 4 of Federal Law of December 7, 2011 N 416-FZ). The quality control of drinking water is carried out through direct measurements of the presence of pollutants and comparison of the detected concentrations with MPC (maximum permissible concentration) for drinking water (SanPiN 2.1.4.1074-01, Decree of the Government of the Russian Federation of 06.01.2015 N 10). To select a rational water quality control plan, the following aspects must be taken into account:

- Choosing a mismatch value
- Risk accounting to consumers (population)
- Opportunity and feasibility of continuous monitoring

On the basis of Article 23 of paragraph 5 (Federal Law of December 7, 2011 N 416-FZ), if the average levels of drinking water samples after water treatment taken during the calendar year do not meet the drinking water quality standards, local governments are required to take measures to bring the quality of drinking water in accordance with established requirements. This is directly related to capital investments in water treatment technology and infrastructure and further operational costs. The number and frequency of water samples (Table 1) taken for laboratory studies of the presence of inorganic and organic substances in water at a water intake (water source) and before being fed into a distribution network are set in Tables 6-8 (SanPiN 2.1.4.1074-01). In the distribution network, the definition of inorganic and organic substances is not standardized; we are only talking about the mandatory determination of microbiological and organoleptic indicators. Risk accounting for the end user of water from centralized water supply systems (population) is associated with the need to assess the risks of the effects of typical pollutants on health.

Table 1. Sampling rate data for the analysis of inorganic and organic impurities in the water of surface water sources and before the water enters the distribution network serving 100,000 residents (SanPiN 2.1.4.1074-01)

Sampling Place	Number of samples
Water source at the water intake site	4
Before water enters the distribution network	4

The basis for the selection of drinking water treatment technologies is the results of a qualitative assessment of the type and quality of the water supply (for example, "contaminated surface water, protected groundwater"). Technology-specific targets are most often applied to microbial and chemical risk factors.

Results

A risk assessment may consist in distinguishing between significant and less significant hazards or events. The risk can be described by determining the likelihood of a hazard (for example, an undoubted, probable, unlikely occurrence) and assessing the severity of the consequences if the danger does occur (for example, minor, serious, catastrophic) (Table 2). In accordance with the Guidelines for ensuring the quality of drinking water (World Health Organization), safety targets associated with a particular technology are set in the form of recommendations used in the water treatment of drinking water sources of drinking and domestic water supply.

Table 2. Options for determining categories of probability and severity of consequences that can be used to assess public health risk

Categories	*Class*	*Notes*
Event Definitions:		*Frequency of occurrence:*
Almost certainly	*5*	Once a day
Probably	*4*	Once a week
With moderate probability	*3*	Once a month
Unlikely	*2*	Once a year
Occasionally	*1*	Once every 5 years
Severity of the consequences:		*Effects:*
Catastrophic effects on public health	*5*	Exposure to chemical composition with excess MPC margin
Significant impact	*4*	The impact on the chemical composition within the safety factor MPC
Moderate effects on organoleptic properties	*3*	Effect on organoleptic properties
Low impact	*2*	Exposure without exceeding standards
Little or no impact	*1*	No or no exposure

Based on the classification of risks, control measures (barrier or protective) that prevent pollution can be ranked according to their importance. Various semi-quantitative and qualitative methods can be used to classify risks (Table 3). (R 2.1.10.1920-04; Grodzensky, Popov, 2014).

Table 3. Examples of hazardous events and related hazards in assessing drinking water treatment technologies (Samburskiy, Pestov, 2017; Spellman, 2017)

Dangerous event	**Hazards**
Non-compliance with the regimes of sanitary protection zones of a water source	In accordance with the characteristics of the catchment area - an unpredictable change in water quality.
Power outages	- Interruptions in water treatment; - No water disinfection
Inconsistency with the regulatory performance of water treatment facilities. Bypass operation - bypass	Overloading of water treatment facilities. Insufficient quality of water treatment.
Violation of water disinfection technology	- Reliability of the disinfection system; - Formation of disinfection by-products
Water treatment system failure	Unprepared water.
Use for water treatment of reagents and materials that do not meet the design documentation, do not meet the standard, the requirements of sanitary rules	Pollution of the water supply system and reduced quality of drinking water. Chemicalization of drinking water, the need for additional monitoring of quality indicators of drinking water

Clogged filters. Insufficient filter load	Inadequate removal of suspended particles, secondary pollution and reduced quality of drinking water.
Vandalism, violation of the rules of anti-terrorism security	Pollution or loss of water supply.
Failure of instrumentation.	Lack of water treatment process control
Telemetry (observation).	Loss of communication with the object of control.
Emergency situations: fire; explosion, flood	Violations in water treatment technology. Termination or limitation of the operation of wastewater treatment plants.

Table 4. Matrix for assessing the reliability of water treatment technology based on risk determination by a semi-quantitative method

	The presence of exposure and its severity				
Frequency of risk	Little or no impact	Low impact	Moderate effects on organoleptic properties	Significant impact	Catastrophic effects on public health
	Class 1 Points	**Class 2**	**Class 3**	**Class 4**	**Class 5**
Almost certainly (once a day). **Class 5**	5	10	15	20	25
Probably (once a week). ***Class 4***	4	8	12	16	20
Moderate (once a month). ***Class 3***	3	6	9	12	15
It is unlikely (once a year). ***Class 2***	2	4	6	8	10
Occasionally (once every 5 years). ***Class 1***	1	2	3	4	5

When using a matrix for risk assessment as a criterion for assessing water treatment technology based on the use of a risk assessment methodology, expert opinion plays a significant role, which allows one to judge the risks to public health arising from hazardous factors or events (Table 3.4).

After determining the value of the risk indicator (Table 5), it is necessary to determine whether the risk is under control and what control measures are provided and / or implemented. If technology vulnerabilities exist, improvement programs should be developed through short-, medium-, or long-term measures to mitigate the likelihood or severity of the consequences.

Table 5. Semi-quantitative risk indicators

Risk points	***≤6***	**7-9**	**10-15**	**≥16**
Risk class	*Low*	*Medium*	High	*Very high*

The risk class corresponding to the "Very High" position is not acceptable for the operation of a water supply company. The parameters presented in table 6 can serve as parameters for determining the priority of risk.

Table 6. Parameters for prioritizing risk

Priority	Risk profile	Note
Explicit Priority	Significant risk	The risk needs further study. It is necessary to determine the effectiveness of existing control measures. Additional control measures are required.
There is no certainty that a probable event may lead to a risk.	Uncertain risk	The need for additional research on the capabilities and characteristics of technology.
Not priority	Insignificant risk	Risk will be considered when improving technology.

Table 7. Health risk assessment using chemicals present in drinking water

Carcinogenic substances		
Individual lifetime carcinogenic risk of CR (R 2.1.10.1920-04)	Risk characterization	Measures necessary to reduce risk
$<10^{-6}$	Inconsequential	Not required
$>10^{-6}$-10^{-5}	Vague	The increase in the multiplicity of definitions of priority risk-forming substances
$>10^{-5}$	Essential	Immediate risk mitigation measures over the period due to the severity of unacceptable risk
Non-carcinogenic substances		
Hazard ratio HQ (R 2.1.10.1920-04)	Risk class	Measures necessary to reduce risk
<0,1	Inconsequential	Not required
>0,1 – 1,0	Vague	Risk is taken into account due to priority substances coming from other environments.
>1,0	Essential	The multiplicity of production control for priority risk-forming substances is increasing.

Table 8. Health Risk Assessment Based on Water Source Factor

Risk assessment	**Water source class by GOST 2761-84**	**Compliance with the regime (SanPiN 2.1.4.1110-02)**	**Compliance with requirements (SanPiN 2.1.5.980-00. 2.1.5)**	**Compliance (SanPiN 2.1.5.1059-01; SanPiN2.1.7.1287 -03)**
Inconsequential	1	The presence of 3 zones of Sanitary Protection Zones, compliance with the	Compliant	All regulatory documents are followed.

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		sanitary regime in them		
Vague	2	Lack of 3 zones of Sanitary Protection Zones	Agreed upon	Only respected (SanPiN 2.1.5.1059-01)
Essential	3	Lack of Sanitary Protection Zones	Not agreed	Documents not complied with

Table 9. Health risk assessment (R 2.1.10.1920-04; Chemistry. Environment. Health) due to the drinking factor determined by water treatment

Risk assessment	**Risk criteria due to water entering the network after water treatment**	**Construction Schedule**	**The quality of reagents, downloads, materials**	**Production control**
Inconsequential	Low in terms of hazard coefficient and individual lifetime risk	Agreed with the authorities of Rospotrebnadzor	Concentrations of substances in aqueous extracts and extracts less than 0.1 MPC	Control methods provide sensitivity less than and at the level of 0.1 MPC
Vague	Acceptable in terms of hazard coefficient and individual lifetime carcinogenic risk	Agreed with the authorities of Rospotrebnadzor	The concentration of substances in extracts and extracts is less than 0.5 MPC	Control methods provide a sensitivity of 0.5 MPC
Essential	Unacceptable in terms of hazard coefficient and individual lifetime carcinogenic risk	Not agreed with the authorities of Rospotrebnadzor	Concentration in extracts and extracts at and above MPC	Control methods provide sensitivity at the MPC level.

Table 10. Health risk classification due to transport and distribution of water

Risk class	Residual Reagent Levels	Flushing from piping materials	Bio-formation	Quality Control Efficiency
Inconsequential	Below concentrations equivalent to reference doses	Below concentrations equivalent to reference doses	Low	Conforms to all measured indicators
Vague	At concentrations equivalent to reference doses	At concentrations equivalent to reference doses	Average	Conforms to priority indicators
Essential	Above MPC	Above MPC	Intense	Not in compliance with controlled indicators

Further analysis of water treatment technologies based on the use of a population health risk assessment methodology, taking into account the list of hazardous events and related hazardous factors, will justify the choice of the most suitable technology for specific conditions. The effectiveness of the implementation of modernization projects (implementation of innovative water treatment technologies) (*Res*) is assessed by the level of achievement of an acceptable / targeted individual and / or population health risk according to formula (1) (MR 2.1.4.0143-19):

$$Res = \frac{R\,after}{R\,target}, \qquad (1)$$

where

R after - risk (individual and / or population) after the implementation of modernization projects (implementation of innovative water treatment technology);
R target - acceptable / target risk level.

The modernization project (water treatment technology) is considered effective at *Res*≤1. If there are several alternative water treatment technologies for one object, the effectiveness of each technology (*Eff*) is evaluated according to the formula (2):

$$Eff = \frac{\Delta R}{Z(k)+Z(oper)}, \qquad (2)$$

where

ΔR – the difference in the values of individual or population risk before and after the implementation of the modernization project (introduction of innovative water treatment technology);
Z – capital (k) and annual operating (oper) costs for the implementation of the project to modernize the water supply system.

To calculate the costs in formula 2, we suggest using the developed methodology for assessing the cost of the life cycle (CLC) (Samburskiy, Bazhenov, 2018).

A complete view of the fair value equation, taking into account the discounted costs over time, is represented by the formula:

$$CLC = \sum_{t1}^{n} \frac{CAPIT\,(C_{ic}^{L+N} + C_{ic}^{PR} + C_{ic} + C_{in})}{(1+r)^n} +$$

$$+ \sum_{t2}^{n} \frac{OPERAT\,(C_e + C_o + C_m + C_s + C_{env})}{(1+r)^n} + C_d$$

(3)

where n – Billing period, years; t1, t2 – the beginning of the stages of implementation of capital and operating costs;

CAPIT – The amount of capital expenditures for items of constituent elements of the CLC;

C_{ic}^{L+N} – Part of the one-time capital expenditures for the acquisition of a land plot (L - land), the cost of obtaining permits and the cost of connecting to other structures and engineering networks of water supply, heat supply, electricity, gas supply (N - network)

C_{ic}^{PR} – Part of the capital costs associated with the provision of design, engineering, or research and development work on the development of design, technological documentation;
C_{ic} – Initial capital cost (general construction work, price of purchased equipment, cost of the technological system with this equipment);
C_{in} – Cost of installation and commissioning costs (construction and installation and commissioning);

OPERAT– The amount of operating costs under the articles of the constituent elements of the CLC;

C_e – Cost of electricity consumed;
C_o – the cost of the service or the current costs of the staff;
C_m – Cost of repair, service and maintenance costs (routine maintenance); for regular consumption of goods (reagent or material);
C_s – Cost of losses from unforeseen downtime and lost products;
C_{env} – Cost of environmental protection and damage prevention;
C_d – Cost of expenses at the end of the billing period “n” of the CLC;
Cd - Cost of expenses at the end of the billing period “n” of the LC;
C_d – Cost of the costs of decommissioning a water supply and disposal facility, including restoring the environment minus the cost of reuse materials.

i – Interest rate (for example, a bank accepted taking into account deposit rates of banks of high reliability category), share of units;
r = (i–p) – Discount rate, shares units;
R – Discount coefficient, shares units.

It is necessary to reduce the data obtained by the options to a common table, at the end of which the values of the total value of the CLC are indicated (Table 11).

Table 11. Calculation results

Components of CLC in the modernization option	Option 1: rebuild concrete, shift the network, do not change equipment	Option 2: provide a barrier function for metals; replace equipment; change the disinfection mode to UV	Option 3: ensure the removal of metals, replace equipment, change the disinfection mode to ozonation + sorption + UV
C_{ic}^{3+C}	not considered according to the technical specifications		
C_{ic}^{PR}, million rubles	5,5	45	58
C_{ic}, with the price of equipment	460	1250	2150
C_{in}	58	490	750
CAPIT	523,5	1875	2958
C_e	12800	10850	14100
C_o	not considered according to the technical specifications		
C_m	250	150	4550
C_s	1550	-	-
C_{env}	25	15	15
C_d	not considered according to the technical specifications		
OPERAT	14625	11015	18665
CLC	15148,5	**12980**	21623

Discussion

Ensuring the quality of drinking water of centralized water supply is impossible without taking into account the risks arising from the entire technological process. Water quality in a water source, features of water treatment technologies; final requirements for water supply safety should form a single system of factors. Considering the fact that this system of factors is in the field of view of various areas of legislation (hygienic, technological, metrological components), the proposed tools for assessing health risks, combined with the positioning of risks from technological processes and the risks associated with conducting analyzes confirming the quality of drinking water, should be the basis for the selection of technological solutions in the field of water treatment for centralized water supply systems.

Based on the proposed data, it is possible to correctly use the mathematical apparatus when choosing water treatment technologies. This question was not part of the task of this study, nevertheless, on the basis of (Grodzenskiy et al., 2019), which proposed the Modified WaldBoost meta-algorithm to clarify the boundaries of the decision on the classification of objects, we draw attention to the possibility of reducing design costs for a given accuracy of classification results water treatment facilities. The use of such algorithms reduces the duration of the corresponding complex calculations in the presence of weak classifiers, which include the initial data for the choice of water treatment technologies.

The introduction of a risk-based approach into practice will ensure compliance with hygienic requirements for water quality of centralized drinking water supply systems. A comparative analysis of water treatment technologies based on the use of the methodology for assessing the risk to public health, taking into account the list of dangerous events and related dangerous factors, will justify the choice of the most suitable technology for specific conditions (Krasnova, Samburskiy, 2018; Prodos et al., 2018). For such purposes, it is advisable to use the semiquantitative matrix method proposed in this paper. This approach allows a qualitative assessment of risks, and the translation of a qualitative assessment into a point scale makes it possible, without additional research, to select technologies based on a preliminary risk analysis. We have proposed the use of a life cycle cost estimation mechanism as a basis for calculating costs in a comparative analysis of water treatment technologies. This toolkit is practically not used in the Russian Federation. Considering that the Federal project “Pure Water” is currently being implemented in the Russian Federation, we believe that the life cycle cost assessment for water treatment facilities should serve as the basis for evaluating technological solutions to select the optimal construction option, taking into account capital and operating costs.

Conclusion

Water quality of centralized drinking water supply is the subject of numerous professional and public disputes, while being an essential component of the quality of life of the population of our country. The safety criterion for drinking water supply is not to exceed the concentrations of pollutants established in (SanPiN 2.1.4.1074-01). An additional aspect that shapes the quality of drinking water supply is the ability to detect relevant pollutants. In the framework of this work, approaches to risk assessment for existing centralized water supply systems are proposed, taking into account the requirements of current regulatory legal acts. Thus, the risk assessment procedure for the state of centralized water supply systems should take into account the impact of each facility that is part of a centralized water supply system, and also take into account risk-oriented aspects for making decisions on further modernization of facilities, including the choice of technologies based on the cost of the life cycle.

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