Case Studies in Chemical and Environmental Engineering 9 (2024) 100774

Contents lists available at ScienceDirect

Case Studies in Chemical and Environmental Engineering

journal homepage: www.sciencedirect.com/journal/case-studies-in-chemical-and-environmental-engineering

Case Report

Design and construction of wastewater treatment facilities for small sewerage facilities

Valentina Kolpakova [a], Yuliya Yeremeyeva [a], Samal Anapyanova [b], Michael Shevtsov [c], Laura Utepbergenova [d,**], Gulnara Abdukalikova [d], Aisulu Abduova [e], Nursulu Sarypbekova [e], Zhanbolat Shakhmov [d,*]

[a] School of Architecture, Civil Engineering and Energy, D. Serikbayev East Kazakhstan Technical University, 19 D. Serikbayev Str., 070004, Kazakhstan
[b] Department of Water, Land and Forest Resources, The Kazakh State Agrarian Research University, 8 Abay avenue, 050010, Kazakhstan
[c] Institute of Civil Engineering, Pacific National University, 136 Pacific Str., 680035, Russian Federation
[d] Department of Civil Engineering, L.N. Gumilyov Eurasian National University, Kazakhstan
[e] Department of Ecology, M.Auezov South Kazakhstan University, 5 Tauke-Khan avenue, 160012, Kazakhstan

ARTICLE INFO

Keywords:
Small sewerage facilities
Suspended bed
Activated sludge
Coagulation
Wastewater treatment technology
Domestic wastewater
Nitrification and denitrification processes

ABSTRACT

The study investigated the effectiveness of clarification of domestic wastewater of small sewerage facilities in the suspended bed of activated sludge. The research was conducted in semi-production and production conditions on the example of a small sewerage facility of East Kazakhstan region with discharge into the river Yertis. The purpose of the study is to develop an effective scheme of wastewater treatment for small sewerage facilities.

The experimental method was used to study the effectiveness of water clarification. Analytical, systematic, comparative methods, as well as methods of mathematical statistics were used to process the experimental results.

The results showed the effectiveness of wastewater treatment in suspended bed of activated sludge flakes sludge. The obtained treatment effect in semi-production and production conditions is comparable with the effect of additional wastewater treatment on sand filters. The treatment effect in semi-production conditions for suspended solids was in the range from 87.5 % to 92 %, and for BOD_5 in the range from 70 % to 72 %. For the application of this technology in production conditions, it was found that the optimal height of suspended bed from 2 to 2.5 m, and the speed of upward water flow from 0.2 to 0.7mm/sec. At the same time, the residual concentration of suspended solids is in the range of 5–10 mg/l.

Treatment with the use of aeration zones and suspended bed of activated sludge can be used for effective clarification of domestic wastewater of small sewerage facilities.

1. Introduction

Small sewerage facilities or “small wastewater treatment plants” include small settlements with up to 5000 inhabitants and freestanding buildings (schools, recreation centers, small industrial enterprises) [1].

Over the last two decades, the construction of cottage-type settlements in cities has been developed. Lack of treatment facilities, insufficient efficiency of treatment, associated with the specificity of these objects, leads to the growth of accidents, pollution of water sources.

Creation of comfortable living of people causes the need for low capacity treatment facilities. It is also necessary to adapt existing and search for new technologies for wastewater treatment of small sewerage facilities.

When treating wastewater from such facilities it is necessary to take into account their peculiarities.

1) Wastewater arrives at treatment facilities very unevenly during the day. At night their quantity can be practically equal to zero. There may be volley discharges of wastewater, which are practically impossible to prevent. In the design of small sewage treatment plants, sewage volley discharges should be given special attention.

* Corresponding author.
** Corresponding author.
E-mail addresses: utepber78@mail.ru (L. Utepbergenova), zhanbolat8624@gmail.com (Z. Shakhmov).

https://doi.org/10.1016/j.cscee.2024.100774
Received 2 April 2024; Received in revised form 20 May 2024; Accepted 22 May 2024
Available online 23 May 2024

2) Due to the irregularity of wastewater inflow, its composition changes, which complicates and reduces the effect of its treatment. There is a need for additional treatment. As a rule, aftertreatment facilities are energy-intensive and difficult to operate.

In most cases, small sewerage facilities are remote from centralized wastewater disposal systems. Modern requirements for landscaping and environmental protection dictate the need for wastewater treatment systems. These systems should have good technical and economic indicators and high treatment efficiency.

For small settlements both centralized and decentralized schemes of wastewater disposal with their further treatment are envisaged.

The author concludes that it is necessary to change the centralized approach to wastewater treatment in small settlements to the principle of distributed treatment in a place as close as possible to the source of their formation [2]. Application of this principle will reduce the capacity of the required single treatment facilities. At the same time, the pumping of wastewater between settlements is excluded.

Under conditions of water scarcity, some studies consider the possibility of reuse of treated water. The authors cite the experience of development and adaptation of technologies for treatment of domestic wastewater from rural communities in Jordan for its reuse for irrigation [3]. They considered the following technologies: septic tank followed by batch sand filter; septic tank followed by wetland; and UASB-hybrid reactor; retractable sand filter (DCSF); septic tank with aerobic biochar filter; bioreactor with vertical flow and recirculation.

The article considers the treatment of domestic wastewater of tourist areas with changing flow rates of incoming wastewater [4]. The treatment technology includes several stages. The first one is a septic tank, the second one is injection into wells with sand-gravel and zeolite loadings.

The authors suggest for decentralized systems to apply wastewater treatment in an anaerobic reactor with baffles based on corrugated PVC [5]. With this technology, the efficiency of organic matter removal was 77–81 %. The average treatment effect on suspended solids is 76–83 %. This technology has low operating costs compared to activated sludge process. However, the capital costs of construction of treatment facilities increase. This is due to the large size of the treatment plant due to the duration of treatment.

At most of the treatment plants at the wastewater outlets there are exceedances of the normative values for BOD_5, suspended solids, nitrogen and phosphorus. Removal of biogenic pollutants from wastewater of small sewerage facilities is a labor-intensive process.

The authors proposed a way to reduce the concentration of phosphorus and nitrogen using simultaneous nitrification and denitrification processes in aerobic reactors [6]. At the same time, the aeration intensity was reduced. In this technology, chemical pretreatment with Fe^{3+} was applied. The average removal efficiencies of organic matter and phosphorus were 51.1 and 74.1 %, respectively.

This technology increased treatment efficiency and reduced energy consumption.

The issues of energy consumption in wastewater treatment are considered in the article [7]. The authors presented the analysis of energy consumption and reliability of operation of 8 wastewater treatment plants of small settlements with capacity from 60 to 4400 m^3/day. Five different treatment technologies, including aeration with activated sludge, are considered. The most energy consuming technology is the one using chemicals and filtration. The lowest energy consumption is the technology of “Laguna” complex, where purification takes place in conditions close to natural.

An example of wastewater aftertreatment in lagoons is given by the authors in the article [8]. The scheme of treatment of domestic wastewater of a small sewerage facility is considered. Wastewater undergoes mechanical treatment, biological treatment in aeration tank and secondary settling tanks. After that it enters the lagoons - evaporators. Insufficient treatment in secondary settling tanks leads to accumulation of sludge at the bottom of lagoons. The authors proposed to reconstruct secondary sedimentation tanks into clarifiers with suspended sludge layer. This will allow to obtain water with concentration of suspended solids and BOD_5 in clarified water in the range of 2–6 and 5.6–8.3 mg/l, respectively.

Thus, the technology of wastewater treatment of small sewerage facilities is developing in two directions: improvement of biological treatment and additional treatment of biologically treated wastewater.

The main method of household wastewater treatment is biological methods. They are the most environmentally friendly. Wastewater treatment can be carried out in aeration tanks. Separation of activated sludge flakes from water after aeration tanks is carried out mainly by gravitational method in secondary settling tanks [9]. Analysis of treatment plants operation shows that at the outlet of secondary settling tanks the required effect of water clarification is not achieved. In most cases, the concentration of suspended solids and BOD_5 is up to 25–30 mg/l, the purification effect varies from 40 to 56 %. This makes it necessary to install additional aftertreatment facilities. Pretreatment can be carried out on sand filters and microfilters. At additional treatment a high effect of water clarification is achieved: the concentration of suspended solids is reduced to 5–8 mg/l, and BOD_5 to 8–10 mg/l. These facilities have disadvantages: they are difficult to operate, energy-intensive due to washing of the load by reverse water current. This leads to an increase in the cost of water treatment.

To achieve the required concentrations of BOD_5 and suspended solids after biological treatment, a number of authors propose the use of suspended bed treatment technology. The suspended bed is formed from activated sludge flakes.

The technology of water treatment with the use of a clarifier is considered [10]. The clarifier consists of a body, a flotation chamber unit, suspended bed and thin-layer sedimentation chambers. There is an electromagnetic treatment system to enhance the effect of flake enlargement and disinfection.

The idea of clarification in a suspended bed was first suggested by Prof. C. Azerier in 1930. Clarifiers have been widely used as the first stage of natural water clarification instead of settling tanks [11]. The author presents the principle of operation and calculation of suspended sludge clarifiers for water purification.

The study of unsteady characteristics of particle motion in the contact mass of the clarifier reactor was carried out by scientists [12]. They considered a model of the filtering process in the contact mass of fluidized bed for natural water treatment.

Processes of separation of concentrated sludge mixtures in a suspended sludge bed were considered in Ref. [13]. The feasibility of the sludge separation method in suspended bed of activated sludge was theoretically substantiated. The mechanism and established the main factors, affecting the formation and operation of the suspended bed. The height of the suspended bed was maintained within 1.0 … 2.0 m. Intensification of the process of separation of concentrated sludge mixtures was carried out due to upward-downward flow distribution to increase the productivity of the facility.

For intensification of water treatment in the suspended bed in Ref. [14] the author recommends using a coagulant and a flocculant. This contributes to the consolidation of contaminants. Purification is carried out in a double suspended bed fluidized bed reactor. With this purification technology, a high degree of suspended solids removal (more than 99 %) was achieved.

The efficiency of water clarification in the suspended bed depends on maintaining a certain height of the suspended bed.

The authors present the factors influencing the permissible limits of sludge mixture circulation velocity for an airlift reactor - clarifier with suspended sludge bed [15]. They define upper and lower limits of circulation velocity for the existence of suspended bed.

There is experience in the development of an innovative hybrid membrane bioreactor with suspended biomass for wastewater treatment [16]. The system consisted of a hybrid circulating bed reactor connected in series with an ultrafiltration membrane module. The COD removal efficiency was up to 95 %.

To reduce phosphorus, the authors conducted studies on a sequencing batch reactor (SBR) for the treatment of chemical effluents [17]. Suspended biomass under aerobic conditions was used for treatment. SBR processes can save more than 60 % of the operating costs compared to a conventional activated sludge treatment process. SBR also has the advantage of enhanced phosphorus removal by combining anaerobic and aerobic processes.

A more uniform wastewater inflow is necessary for the effective operation of treatment plants. Therefore, it is necessary to smooth out the irregularity of wastewater inflow characteristic of small sewerage facilities. This can be achieved by means of sludge recirculation systems from the upper zone of the suspended bed.

The authors noted that abroad the most effective reactors for biochemical processes in wastewater treatment are recognized as airlift reactors (ALR) with internal circulation of sludge mixture [18]. In their work they determined the maximum and minimum permissible values of circulation intensity at different hydraulic loads. They obtained dependencies for determining the main parameters of the suspended bed:

- velocity of the upward flow of liquid in the suspended bed;
- flow rate of the sludge mixture returned from the suspended bed to the circulation flow of the airlift reactor;
- residence time of the sludge mixture in the suspended bed of the clarifier aeration tank;
- maximum hydraulic load on the clarifier.

Experimental determination of modeling parameters of aeration clarifiers with flooded airlift aeration system is presented in Ref. [19]. The results of the study showed that the hydrodynamic parameters required for the operation of the suspended bed in the aeration clarifier with flooded airlift aeration system do not depend on the size of the structure. It is sufficient to observe geometric similarity of the designed full-scale structure.

The authors continued the work on the improvement of the design of the aeration tank sedimentation tank with a renewable suspended sludge layer [20]. The aeration tank with flooded airlift aeration system allows to maintain increased concentrations of activated sludge in the bioreactor with the minimum size of the built-in settling tank. This provides a decrease in energy consumption and an increase in the efficiency of biological treatment.

The authors considered the design features of aeration clarifier with a flooded airlift aeration system [21]. The research results showed that the increase of activated sludge concentration in the suspended bed provides the efficiency of water clarification. This is achieved due to the intensity of circulation of activated sludge.

The mathematical description of hydrodynamic parameters of an airlift bioreactor clarifier was continued by the same authors in Ref. [22]. A stationary two-dimensional problem of fluid motion in an airlift bioreactor-lightener (aeration tank-lightener with a flooded airlift aeration system) was solved by the finite difference method. The formation of a whirlpool zone in the clarifier of the biological reactor is taken into account.

The temperature of clarified water significantly affects the stability of clarifier operation. This issue was studied by the authors of the influence of the temperature of clarifying water [23]. The researchers show that the efficiency of clarifier operation depends on water temperature and sludge index. Analysis of graphs of dependence of residual suspended solids concentration in treated water on the speed of upward water flow shows a decrease in the silt index from 120 to 137 cm^3/g to 50–58 cm^3/g with a simultaneous increase in the wastewater temperature from 19.0 °C to 24.5-25 °C. This leads to a significant improvement in water clarification quality. Namely, the residual content of suspended solids in treated water at the speed of upward flow in the clarification zone V = 1.2 mm/s decreases from 11 to 12 mg/l to 3 mg/l.

Researches in the field of domestic wastewater treatment in suspended sludge beds have been carried out by scientists, the results of which are reflected in Ref. [24]. The efficiency of water treatment in clarifiers with suspended sludge bed formed from biofilm flakes or activated sludge is determined by the residual concentration of suspended solids in clarified water. The obtained results show the reduction of suspended solids concentration to 3–5 mg/l and BOD_5 to 6–10 mg/l. At the same time, the cost of water purification is quite low and lower than in the case of additional water treatment on sand filters.

The results of the author's research of the processes of treatment of biologically treated wastewater after biofilters and aeration tanks in clarifiers with suspended sludge bed [25]. The mathematical model of clarification process in suspended sludge bed is developed. The high effect of water clarification comparable with the effect of additional treatment on sandy rapid filters is provided. The concentration of suspended solids ranges from 2 to 6 mg/l, BOD_5 from 2 to 8 mg/l. Achievement of such indicators is provided at the height of suspended layer from 1.0 to 1.8 m and upward flow velocity in the clarification zone from 0.6 to 1.2 mm/s.

The authors presented the results of experimental studies on clarification of biologically treated wastewater in a clarifier with a suspended sludge layer [26]. From the obtained experimental relationships between the technological parameters, the range of upward flow velocity from 0.6 to 1.4 mm/s was established. This provides dynamic equilibrium of the suspended layer from 1.2 to 1.8 m. Under these conditions, the content of suspended solids in clarified water at discharge is less than 5.0 mg/l.

Literature review revealed:

- there is a need to intensify the operation of small wastewater treatment plants;
- lack of data in the study of technology of treatment of biologically treated domestic wastewater in clarifiers with a suspended bed of activated sludge flakes for small sewerage facilities.

Increasing pollution of surface water sources and deterioration of the ecological situation cause an increase in the requirements for wastewater treatment. In this connection, improvement of the technology of treatment of household wastewater with small flow rates is very relevant.

The purpose of this research is expediency of application of technology of treatment of biologically treated domestic wastewater in clarifiers with suspended sludge bed.

Scientific novelty of this work consists in justification of the use of suspended sludge layer of activated sludge flakes in clarification of wastewater.

In the present study, the experimental dependencies of the parameters determining the efficiency of water treatment are studied.

The results of this study can be used in the design and construction of treatment facilities for small sewerage facilities.

2. Materials and methods

2.1. Object of study

The object of the study is biologically treated wastewater after aeration tanks.

Quality indicators of initial wastewater are given in Table 1.

The studies were conducted under semi-production and production conditions.

2.2. Parameters under study

The following dependences were studied during the research under semi-production conditions:

Table 1
Quality indicators of initial wastewater.

Quality indicators	Unit of measurement	Significance
Suspended solids	mg/l	20 - 60
Water temperature	^0C	15 - 20
pH		7,0–7,5
BOD_5	mg/l	15 - 25
Dissolved oxygen	mg/l	4,5–6,0
NH_3	mg/l	3–25
NO_2	mg/l	0,3 - 0,45
NO_3	mg/l	3 - 6

- concentration of activated sludge in suspended bed ($C_{sus.l}$, g/l) on the velocity of upward water flow (V_{asc}, mm/s);
- concentration of residual suspended solids in clarified water (C_{cl}, mg/l) from the upward water flow velocity (V_{asc}, mm/s);
- influence of suspended activated sludge layer height ($H_{sus.l}$, m) on the residual suspended solids content in clarified water (C_{cl}, mg/l).

The effect of water clarification, parameters of clarified water: dissolved oxygen concentration, NH_3, NO_2, NO_3 content, acidification, BOD_5, COD, sludge index (J, cm^3/g) were determined. The biocenosis of activated sludge of the suspended bed was studied during the research.

When conducting research in production conditions, the dependence of the concentration of residual suspended solids in clarified water (C_{cl}, mg/l) on the speed of upward water flow (V_{asc}, mm/s) was studied.

The dependence studies were carried out in a wide range of changes in the upward water flow velocity ($V_{asc} = 0.6–1.8$ mm/s), suspended bed height ($H_{sus.l} = 0.33–1.8$ m) and suspended solids concentration in clarified water ($C_{en} = 0.02–0.06$ g/l).

2.3. Methods used

The complexity of physical, chemical and hydraulic processes that occur in clarifiers with suspended sludge layer excludes the use of mathematical method.

Therefore, the experimental method was used to study the dependences of water clarification efficiency on the studied parameters.

To process the results of physical experiment used analytical, systematic, comparative methods. To obtain empirical dependencies used methods of mathematical statistics. All measurements and sampling were carried out not earlier than 2–3 hours after the change in the feed water flow rate and, accordingly, the rate of upward water flow.

The activated sludge concentration ($C_{sus.l.}$) and suspended solids content in clarified water (C_{cl}) were determined according to the standard method [27]. The gravimetric weighing method was applied using paper filters with pore size 2–3 μm and membrane filters with pore size 0.45 μm, respectively.

The upward water velocity (V_{asc}) was determined volumetrically at the clarifier outlet. The cross-sectional area of the clarifier and the feed water flow rate were used.

The height of the suspended activated sludge layer was determined by direct measurement using a measuring scale.

Dissolved oxygen concentration was determined by the Winkler method [28]. The content of BOD_5, COD, NH_3, NO_2, NO_3, and acidification were determined according to standard methods [29–31].

Sludge index (J, cm^3/g) was calculated according to the standard method [32]. It was defined as the ratio of the volume of settled sludge in cm^3 to the mass of its dry matter in grams.

The biocenosis of suspended bed activated sludge was studied using a microscope in the hydrobiological laboratory.

The cleaning effect was determined by the formula:

$$E = (C_{en} - C_{ex}) / C_{en} \times 100\%,$$

where C_{en} is the concentration of pollution at the inlet, mg/l;

C_{ex} - concentration of pollution at the outlet, mg/l.

2.4. Studies under semi-production conditions

Studies under semi-production conditions at the pilot plant.

The pilot plant is presented in Fig. 1.

The clarifier column is made of organic glass with a diameter of 200mm and a height of 4.0 m.

The operation of the unit was carried out as follows. Source water by pump (2) from the channel (3) through the pipeline (4) was fed to the flow stabilizer (5). From the stabilizer (5), the water was supplied to the bottom of the clarifier (1) by pipeline (6). The source water was upwardly flowing up the clarifier column. At certain velocities of the upward flow a suspended layer of activated sludge flakes was formed. When water passed through the suspended bed, biological purification processes and retention of activated sludge flakes took place. The clarified water was discharged from the upper zone of the clarifier through the pipeline (7) into the clarified water channel (8). Excess activated sludge flakes were discharged from the upper level of the suspended layer through the pipeline (9) into the tank (10). The discharge was regulated by means of gate valve 11. Water supply to the clarifier was regulated by gate valves 12 and 13.

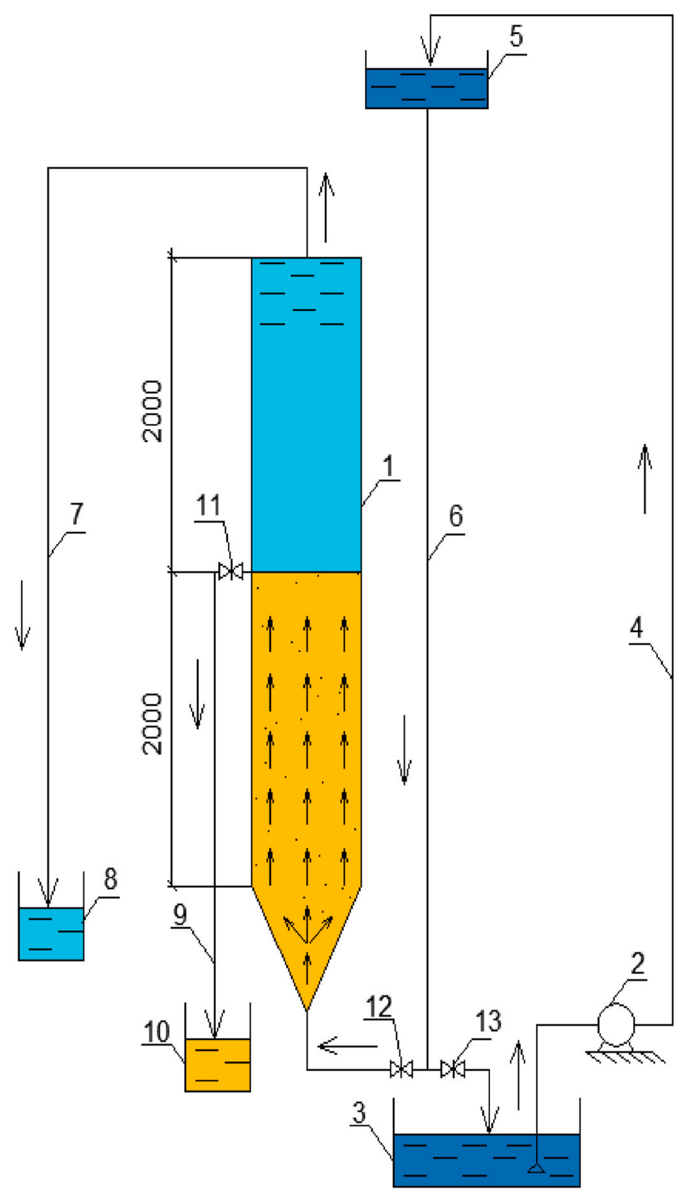

Fig. 1. Schematic diagram of the experimental setup.

2.5. Research in industrial settings

Studies were conducted at one of the small objects of East Kazakhstan region with average daily flow rate of domestic sewage 16.7 m^3/day. Inflow during the day is highly irregular.

Wastewater treatment was carried out in a septic tank of three chambers with a total capacity of 26m^3. After the septic tank the wastewater is discharged into the river Yertis. Concentration of treated wastewater was 100.5 mg/l, suspended solids - 125 mg/l. This does not meet the requirements for discharge into the water body - the Yertis River. Such water quality at the discharge has an anthropogenic impact on the water source.

Due to the fact that the septic tank does not provide the proper treatment effect, a project was developed and a full biological treatment plant was constructed. The throughput capacity of the treatment plant is up to 24 m^3/day. In order to smooth the unevenness of wastewater inflow, a device for recirculation of water and activated sludge flakes from the upper zone of the suspended layer of the facility is provided.

The following factors were taken into account when developing the design of facilities for wastewater treatment of small sewerage facilities:

1) conditions of treated effluent discharge;
2) mode of wastewater inflow to the treatment facilities.

When developing designs of clarifier with suspended sludge bed, it is necessary to create optimal conditions for suspension formation, water treatment, dynamic equilibrium of the contact medium and sludge removal. This will ensure:

1) uniform distribution of flows over the live cross-section at the water inlet and outlet;
2) optimal size and density of particles of the contact medium, sufficient particle settling rate;

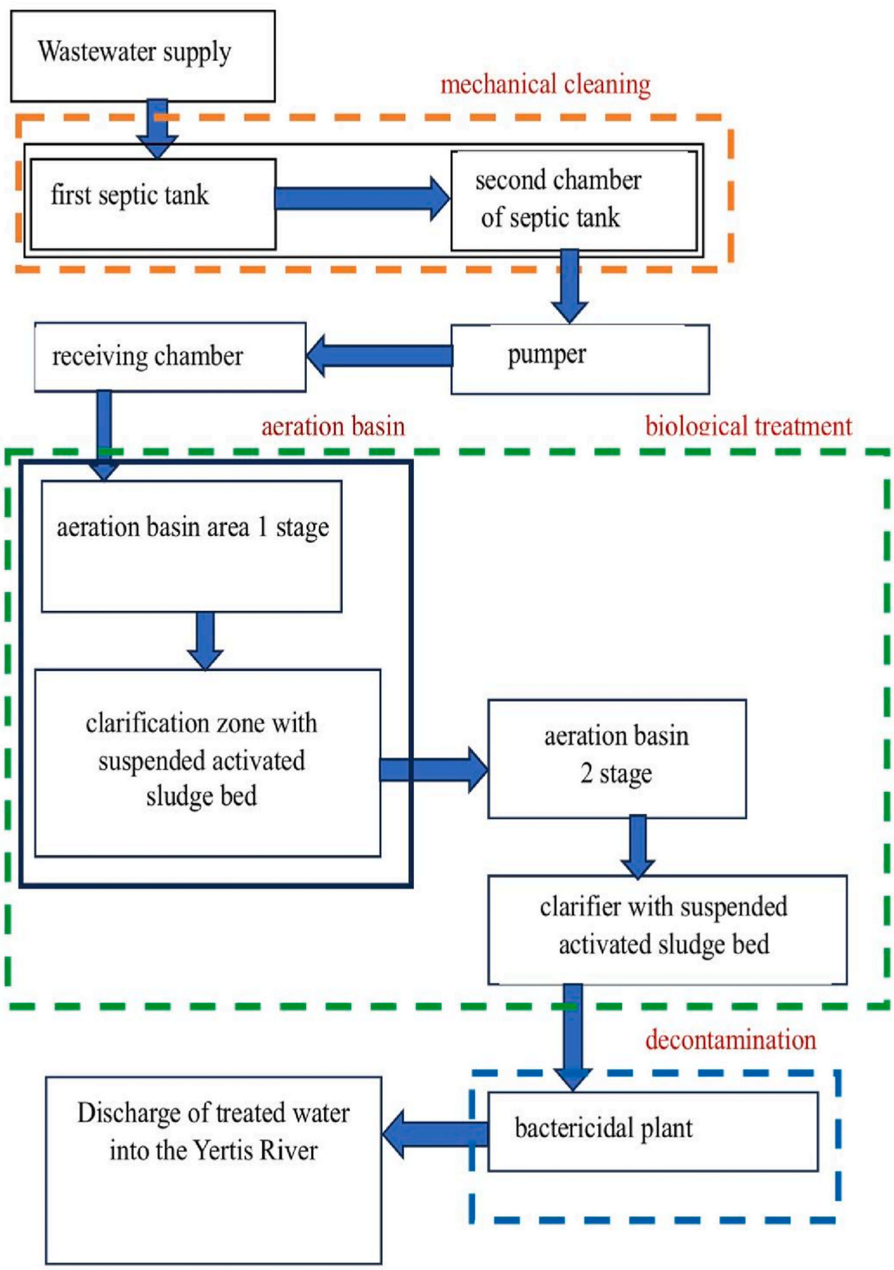

Fig. 2. Technological scheme of the treatment plant.

3) removal of air from the water to eliminate the process of barbotage and destruction of the integrity of the suspended layer;
4) absence and minimum of stagnant zones and local suction of clarified water from the contact medium in the upper zone of the suspended bed;
5) uniform removal of excess suspended solids from the suspended bed;
6) maximum sludge thickening with minimum water losses for its removal;
7) possibility of operation with interruptions and fluctuations in wastewater inflow;
8) simplification and cheapening of constructions at preservation of clarification efficiency.

In East Kazakhstan Technical University named after D. Serikbayev (Republic of Kazakhstan) developed a new technology of water treatment using clarification in suspended sludge layer. This technology is presented in Fig. 2.

The main structures of the developed technological scheme are: aeration tank - clarifier, aeration tank, clarifier with suspended activated sludge bed.

Aeration tank - clarifier is round in plan and cylindrical in shape. It works on the principle of aeration tank - mixer with subsequent clarification of water in a layer of suspended activated sludge. The facility has aeration zone and clarification zone with suspended sludge layer. The aeration zone occupies the central part of the plant and the clarification zone is located around it. The aeration zone is supplied with air

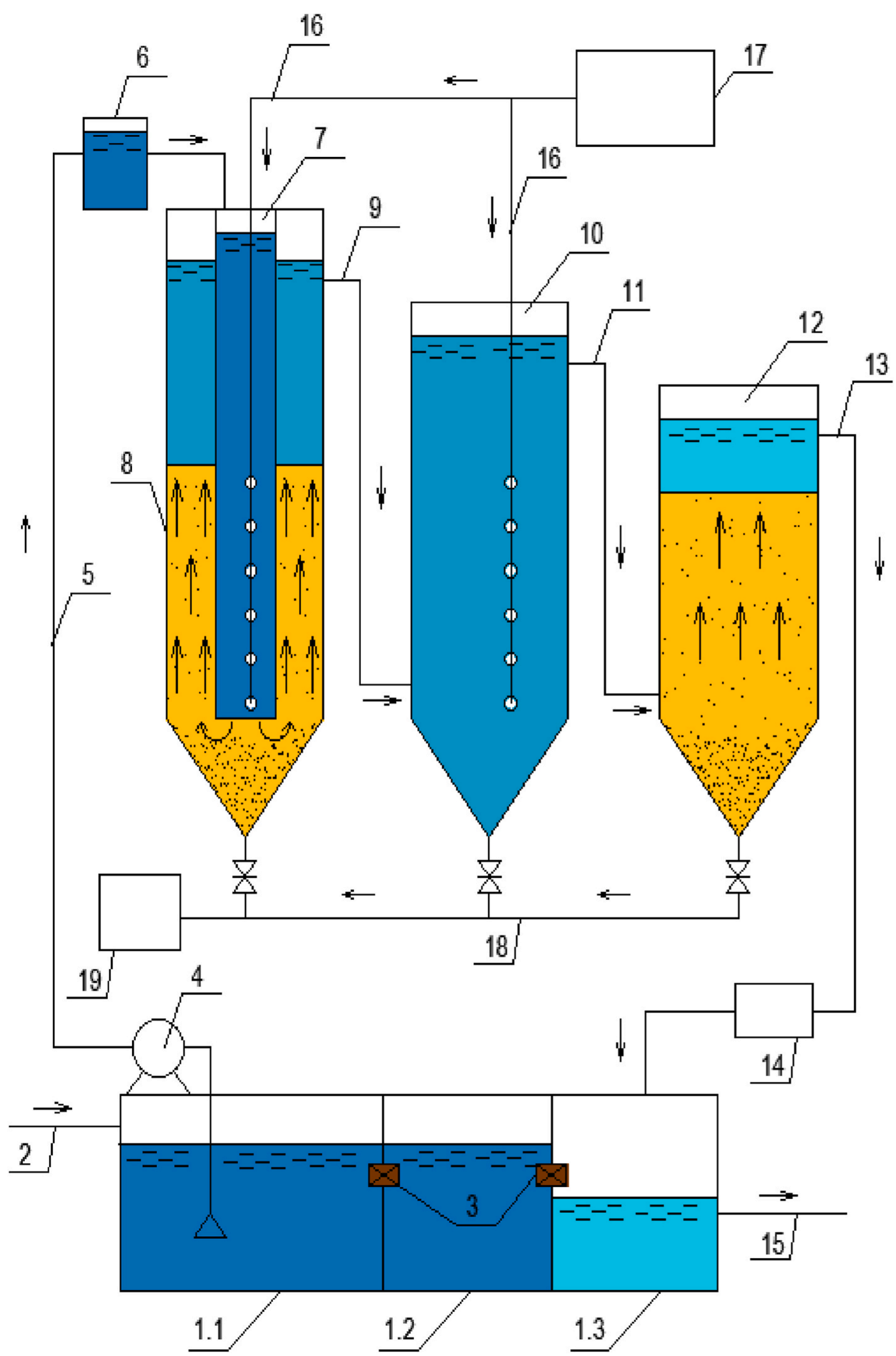

Fig. 3. Schematic diagram of the treatment plant facilities.

for oxidation of organic matter.

Fig. 3 shows a schematic diagram of the treatment plant facilities.

The process of wastewater treatment proceeds as follows.

Mechanical treatment of wastewater is carried out in the existing septic tank.

Wastewater flows through the pipeline (2) into the first septic tank chamber (1.1), which performs the role of primary sedimentation. Through the window (3) the wastewater flows into the second septic tank chamber (1.2) in case of overfilling of chamber 1.1. By pumps (4) through the pipeline (5) the water is delivered to the receiving chamber (6) for smoothing of unevenly incoming wastewater. Then the water enters the aeration tank zone (7) of the first stage. After biological treatment, the wastewater enters the clarification zone (8) from the suspended bed. The water moves through the suspended bed from bottom to top. Coagulation of activated sludge flakes takes place in the suspended bed. The clarified water flows through the pipeline (9) to the base of the second stage aeration basin (10) for biological treatment. The water passes from bottom to top and enters the circular trough of treated water. Further water through the pipeline (11) enters the lower part of the third stage treatment facility - clarifier with suspended bed of activated sludge (12).

Wastewater, passing the suspended layer, is subjected to deeper purification. Then through the pipeline of purified water (13) enters the septic tank chamber 1.3. A bactericidal water disinfection unit (14) is provided on the pipeline (13). From the septic tank chamber (1.3) the treated wastewater is discharged by gravity flow into the river Yertis through the pipeline (15).

Compressed air is supplied to the aeration zones (7) and (10) through ducts (16) from the blower (17). This is necessary for the biological treatment processes. Excess sludge from the plant is discharged into a tank (19) via pipeline (18).

In this treatment technology, the nitrification process takes place in the aeration zone and the denitrification process in the suspended sludge zone. This allows to obtain high quality of treated water.

3. Results and discussion

3.1. Results of the study under semi-production conditions

The results of experimental studies showed that the use of a clarifier with a suspended sediment layer of activated sludge flakes will intensify the process of water clarification. The concentration of suspended solids in the clarified water was within the range from 2 to 6 mg/l, BOD_5 within the range from 5.6 to 8.3 mg/l at the rate of upward water flow from 0.6 to 1.4 mm/s. The concentration of the sludge mixture fed into the clarifier was C_{en} = 50–200 mg/l. The obtained effect is comparable to the effect of aftertreatment on sand rapid filters.

The main regularities obtained in semi-production conditions are given below.

The experimental graphical dependence of $C_{sus.l} = f(V_{asc})$ is presented in Fig. 4.

The graph shows that with decreasing velocity of upward flow (V_{asc}) in the suspended bed, the sludge concentration ($C_{sus.l}$) increases, while with increasing velocity of upward flow it decreases. Studies have shown that the dynamic equilibrium of the suspended bed is maintained at upward flow velocities between 0.6 and 1.8 mm/s. At a velocity of less than 0.6 mm/s flakes are deposited on the bottom of the clarifier and compacted, at that, the concentration in the suspended layer ($C_{sus.l}$) is 12.5 g/l. At velocity V_{asc} = 1.8 mm/s and more, the layer is eroded, particles of suspended layer are carried away with the flow of clarified water, in this case, $C_{sus.l}$ was 2.0–2.5 g/l. When changing the velocity of upward flow from 0.6 to 1.8 mm/s, the concentration of activated sludge flakes in the suspended layer was within the limits ($C_{sus.l}$) from 10.0 to 2.5 g/l. The curve $C_{sus.l} = f(V_{asc})$ at increasing the speed of upward water flow from 0.55 to 1.2 mm/s steeply declines. When increasing V_{asc} from 1.2 to 1.8 mm/s curve $C_{sus.l} = f(V_{asc})$ passes into a gentle line, approaching a horizontal straight line.

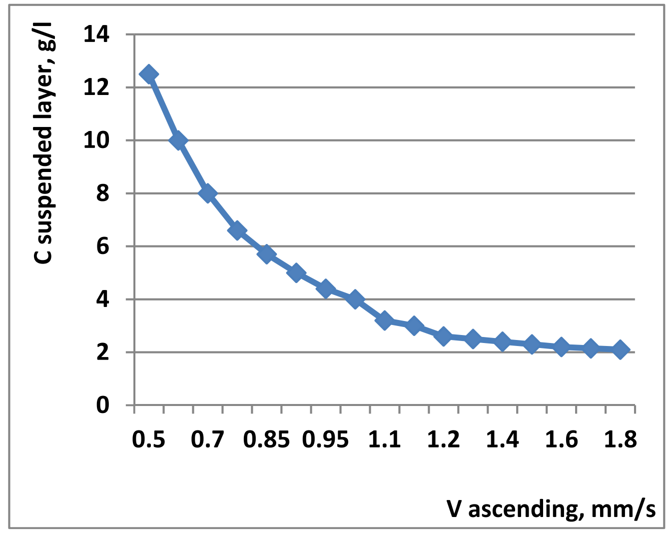

Fig. 4. Graph of the dependence of ($C_{sus.l}$) on (V_{asc}).

Efficiency of wastewater treatment was determined by residual concentration of suspended solids (C_{cl}) in clarified water. Studies were conducted in the same range of upward water flow velocities (V_{asc}) from 0.6 to 1.8 mm/s.

The obtained experimental dependence of $C_{cl} = f(V_{asc})$ is presented in Fig. 5.

As a result of processing the experimental data of the dependence $C_{cl} = f(V_{asc})$, the empirical formula was obtained:

$$y = 8.1233 - 12.8898x + 6.9203x^2 \quad (1)$$

Analysis of the graph showed that when V_{asc} changed from 0.6 to 1.2 mm/s, the residual concentration of suspended solids in clarified water (C_{cl}) was 2–3 mg/l. This is 5–6 times less than after simple sedimentation in secondary sedimentation tanks.

At increasing the speed of the upward flow of water more than 1.2 mm/s of the curve graph is sharply directed upward. In this case, the concentration of suspended solids in clarified water (C_{cl}) also increases sharply. For example, at V_{asc} = (1.2–1.6) mm/s residual concentration in clarified water was C_{cl} = (3–5) mg/l, and at V_{asc} = (1.6–1.9) mm/s was C_{cl} = (5–9) mg/l.

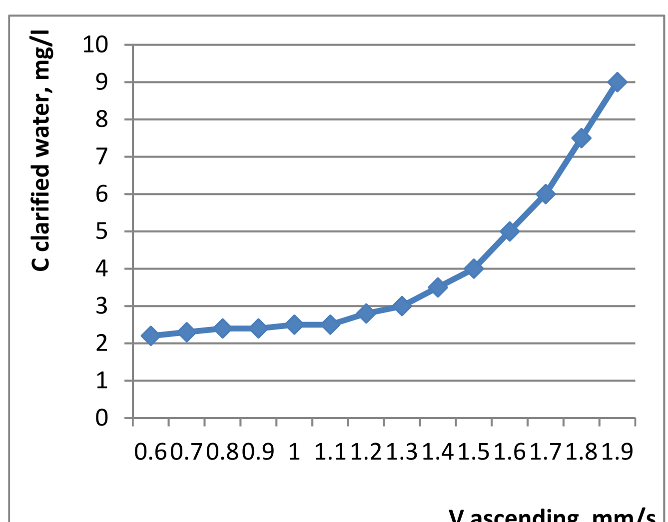

Fig. 5. Graph of the dependence of (C_{cl}) on (V_{asc}).

At further increase of speed of ascending water flow more than 1.8 mm/s residual concentration in clarified water reaches 20 mg/l and more.

According to the results of research the experimental graphical dependence of $C_{cl} = f(H_{sus.l})$, presented in Fig. 6.

An empirical formula was obtained for the dependence $C_{cl} = f(H_{sus.l})$:

$$y = 6.5608-6.9193x+2.0080x^2 \quad (2)$$

From the graph of dependence we can see that the higher the height of suspended sludge layer ($H_{sus.l}$), the lower the residual concentration of suspended solids (C_{cl}) in clarified water. The optimum height of the suspended sediment layer was determined based on the content of C_{cl} in the range from 0.5 to 2.8 mg/l and amounted to 0.6–1.8 m.

Water quality parameters and treatment effect are summarized in Table 2.

Analysis of the data in Table 2 shows that after treatment, the concentration of suspended solids and BOD_5 is less than 10 mg/L. The concentration of suspended solids ranged from 2.5 to 4.8 mg/l and BOD_5 ranged from 4.5 to 7.0 mg/l. The treatment efficiency for suspended solids was in the range of 87.5 %–92 % and for BOD_5 in the range of 70 %–72 %. The treatment effect of the proposed technology is higher than in the traditional scheme with aeration tanks and secondary sedimentation tanks, where the effect is from 40 to 56 %. The quality of treated water after clarifiers with suspended sludge bed is also higher in other indicators.

The sludge index (J) was in the range of 60–64 cm^3/g. This value shows that activated sludge has good sedimentation properties. It also indicates optimal conditions for activated sludge biocenosis in the suspended bed.

The biocenosis of activated sludge in the suspended bed is represented by microorganisms such as: *Cathypha luna -3, Bodo -3, Aspidisca turrida - 7, Aspidisca costata -8, Rotathria marcoceria - 6, Opercularia glomerata -3, Aelosoma -4, Notommate ansata - 3, Zionotus anser-2, Zionotus lamella -3, Vorticella alba -4, Vorticella microstoma -4, Stentor raeseli - 3, Callidina vorax -3, Nematoda -2.*

3.2. Research results in production conditions

As a result of the studies, the dependence of $C_{cl} = f(V_{asc})$, presented in Fig. 7, was obtained.

Fig. 7 shows that with increasing velocity of upward water flow (V_{asc}) the sediment removal into clarified water (C_{cl}) increases. The lowest sediment removal into clarified water 5–10 mg/l is observed when the upward water flow velocity varies from 0.2 to 0.7 mm/s. At the velocity of V_{asc} from 0.7 to 1.0 mm/s, the suspended sediment concentration (C_{cl}) varied from 8 to 15 mg/l. At the same time, the height of suspended activated sludge layer was in the range from 0.5 to 2.5 m. At velocity $V_{asc} = 1.0$–1.2 mm/s the concentration of suspended solids in clarified water was $C_{cl} = 15$–25 mg/l.

Studies of wastewater clarification process in the suspended sludge bed under production conditions confirmed the main regularities obtained under semi-production conditions.

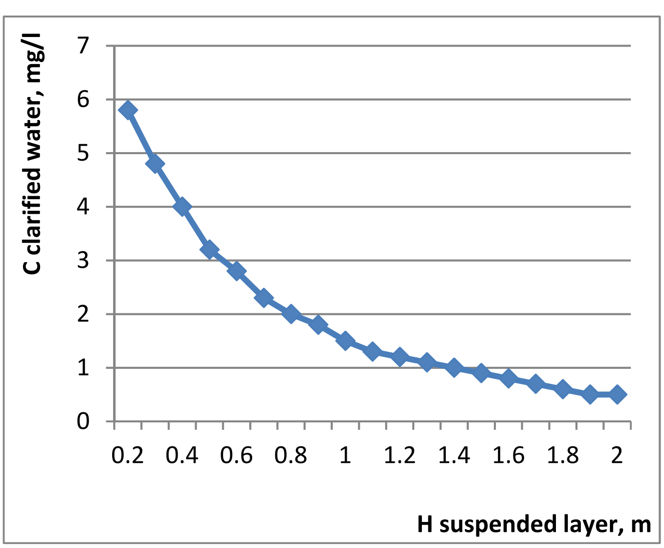

Fig. 6. Graph of dependence of (C_{cl}) on ($H_{sus.l}$).

Table 2
Water quality indicators and treatment effect.

Parameters, indicators	Before cleaning	After cleaning	Cleaning effect, %
Suspended substances, mg/L	20 - 60	2,5–4,8	87,5–92,0
Water temperature, ^0C	15 - 20	9–12	–
pH	7,0–7,5	7,0	–
BOD_5, Мг/л	15 - 25	4,5–7,0	70–72
Dissolved oxygen, mg/L	4,5–6,0	5–6	–
NH_3, mg/L	3–25	10–11	до 56
NO_2, mg/L	0,3- 0,45	0,1 - 0,12	66,7–73,3
NO_3, mg/L	3 - 6	2 - 3	33,3–50,0

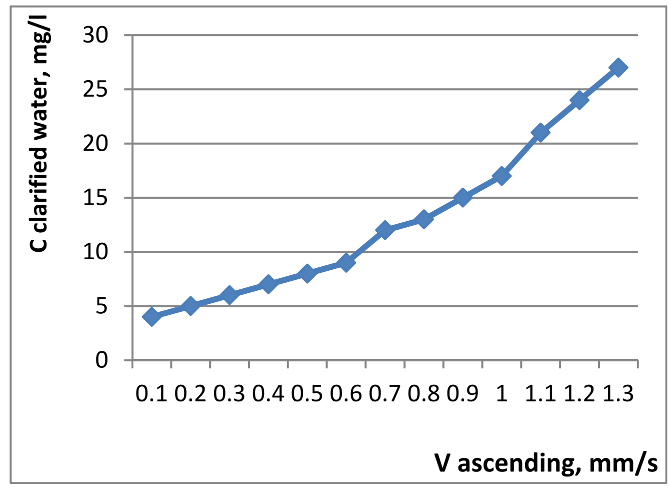

Fig. 7. Graph of dependence of concentration (C_{cl}) on the speed of upward water flow (V_{asc}) at the height of suspended layer $H_{sus.l} = 2$–2.5 m.

4. Conclusion

The study investigated the process of domestic wastewater treatment using an aeration ta clarifier with a suspended sludge bed. The suspended bed was formed from activated sludge flakes. The study was carried out under semi-production and production conditions.

The results of the studies under semi-production and production conditions showed a high treatment effect on BOD_5 and suspended solids, comparable to the effect obtained by the aftertreatment. The suspended solids concentration ranged from 2.5 to 4.8 mg/l and BOD_5 from 4.5 to 7.0 mg/l. After pretreatment, suspended solids concentration decreased to 5–8 mg/l and BOD_5 to 8–10 mg/l. For the other parameters of treated water quality, a high effect is also observed. This is explained by the presence of nitrification processes in the aeration zone and denitrification in the suspended layer.

In the study determined the optimum permissible fluctuations in the speed of the upward flow of water from 0.6 to 1.8 mm/s. In this range of velocities the required efficiency of water clarification is achieved and stable operation of the clarifier with suspended sludge layer is maintained. If the recommended speeds are reduced, sludge sliding is observed, and if the recommended speeds are exceeded, the suspended sludge layer is eroded.

Under semi-production conditions, the optimum suspended bed height was 0.6–1.8 m, with C_{cl} ranging from 0.5 to 2.8 mg/l. Under production conditions, the suspended bed height was 2–2.5 m, with C_{cl} ranging from 2.5 to 4.8 mg/l.

Dissolved oxygen with concentration of 4.5–6.0 mg/l entering the clarifier with wastewater is actively consumed in the suspended bed of activated sludge, providing viability of microorganisms.

Species diversity of microorganisms and their activity allow us to conclude that in the suspended bed of activated sludge is in a viable state and actively participates in the processes of biochemical oxidation of organic pollutants.

The results of research in production conditions confirmed the results of research obtained in semi-production conditions.

Water quality, after the application of the proposed technology of wastewater treatment, meets the requirements for their discharge into rivers. Does not have a negative impact on water bodies. It is implemented at one of the small sewerage facilities of East Kazakhstan region at discharge of treated wastewater into the river Yertis. It allows to reduce the anthropogenic load and negative impact on the aquatic ecosystem of the Yertis River basin in the conditions of industrial development of the region.

This technology can be applied to other small sewerage facilities.

Data accessibility statement

The data that contributed to the findings and conclusions of this study are available upon reasonable request from the authors.

CRediT authorship contribution statement

Valentina Kolpakova: Writing – original draft. **Yuliya Yeremeyeva:** Conceptualization. **Samal Anapyanova:** Investigation. **Michael Shevtsov:** Methodology. **Laura Utepbergenova:** Validation, Project administration. **Gulnara Abdukalikova:** Validation. **Aisulu Abduova:** Writing – review & editing, Resources. **Nursulu Sarypbekova:** Funding acquisition. **Zhanbolat Shakhmov:** Visualization, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

Acknowledgments

We express our deepest gratitude to the reviewers for their detailed reviews and comments, which helped to significantly improve this study.

This study is funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (grant N°. BR21881921 ″Assessment of the water ecosystem of the Yertis River basin under the conditions of industrial development and global processes").

References

[1] SN RK 4.01-03-2013*, Vodootvedenie. Naruzhnye seti i sooruzheniya AO "Kazakhski Vodokanalproekt (2019) 398.
[2] M.M. Pukemo, Factors of effective development of water and sewerage facilities of small settlements, J. Sanitary Eng. (4) (2018) 36–39. https://www.abok.ru/for_spec/articles.php?nid=7012.
[3] Al Arni Saleh, Mahmoud Elwaheidi, Alsamani A.M. Salih, Djamel Ghernaout, Mohammed Matouq, Greywater reuse: an assessment of the Jordanian experience in rural communities, Water Sci. Technol. 85 (6) (2022) 1952–1963, https://doi.org/10.2166/wst.2022.080.
[4] Ismael Vera-Puerto, Hugo Valdés, Christian Correa, Jorge Olave, Valeria Pérez, Carlos A. Arias, Variation of the feeding/resting period in modified vertical treatment wetlands (depth, zeolite as medium) employed for treating rural domestic wastewater in tourist areas, Water Sci. Technol. 88 (6) (2023) 1394–1403, https://doi.org/10.2166/wst.2023.283.
[5] Nadeem Ullah, Zeshan Sheikh, Malik Badshah, Municipal wastewater treatment with corrugated PVC carrier anaerobic baffled reactor, Water Sci. Technol. 87 (3) (2023) 660–671, https://doi.org/10.2166/wst.2022.414.
[6] Xinyuan Niu, Xuejun Bi, Ruihuan Gu, Zhixuan Yin, Benliang Yang, Changqing Liu, Modification of a plant-scale semi-centralized wastewater treatment system to enhance nitrogen and phosphorus removal from black water, Water Sci. Technol. 87 (8) (2023) 2005–2019, https://doi.org/10.2166/wst.2023.100.
[7] Rania Hamza, Mohamed F. Hamoda, Mohammad Elassar, Energy and reliability analysis of wastewater treatment plants in small communities in Ontario, Water Sci. Technol. 85 (6) (2022) 1824–1839, https://doi.org/10.2166/wst.2022.093.
[8] V.P. Kolpakova, M.N. Shevtsov, Y.N. Yeremeyeva, S.B. Anapyanova, Treatment of wastewater of small sewerage, Facilities IOP Conference Series: Earth Envir. Sci. link disabled 988 (5) (2022) 052022, https://doi.org/10.1088/1755-1315/988/5/052022. http://iopscience.iop.org/journal/1755-1315.
[9] V.I. Zyatin, Dvizhenia Zhidkosti V Kolonne Osvetlytelya Vo Vzveshennom Sloe Osadka. Bulletin of DonNABU, Issue 2015-5(115) "Engineering Systems and Technogenic Safety, Makeevka, 2015, pp. 16–22.
[10] Patent RU 2752743 C1, Russia, IPC B01D 21/08 Clarifier for water treatment (variants). Application number: 2020125876, filed. 04.08.2020, published 30.07.2021. Patent holders: Limited Liability Company "Sibvodrazrabotka"./ Demidovich Y.N. https://www.elibrary.ru/item.asp?id=46477712.
[11] N.I. Kulikov, [и др.]. Vodosnabzhenie: Training Manual, Novosibirsk: TsSRNI Ltd., 2016, 704c.
[12] Y.U.L. Scolubovich, M.S. Soppa, N.B. Sineeva, Modelirovanie nestatsionarnyh harakteristik dvizhenia chastits kontaktnoi massy v reaktore-osvetlitele. Izvestiya vysshyh uchebnyh zavedenii, Stroitelstvo 7 (679) (2015) 38–43.
[13] V.I. Zyatin, «Intensifikatsya Protsessa Razdelenia Kontsentrirovannyh Ilovyh Smesei Vo Vzveshennom Sloe». Dis.... Candidate of Technical Sciences, GOU VPO Donbas Academy of Civil Engineering and Architecture, 2016. Makeyevka.
[14] YunXiao Ban, Purification of bathing wastewater by double suspended layer fluidized bed reactor, Water Sci. Technol. 85 (8) (2022) 2375–2388, https://doi.org/10.2166/wst.2022.086.
[15] Viktor Nezdoiminov, Dmitrii Zavorotnyi, Vitalii Rozhkov, Pavel Deminov Permissible parameters for the circulation rate of the sludge mixture in airlift reactor-clarifier with suspended layer. International Scientific Conference on Energy, Environmental and Construction Engineering (EECE-2018) https://doi.org/10.1051/matecconf/201824511009 , 5 December 2018.
[16] P. Artiga a, V. Oyanedel a b, J.M. Garrido a, R. Méndez, An innovative biofilm-suspended biomass hybrid membrane bioreactor for wastewater treatment, Desalination 179 (1–3) (2005) 171–179, https://doi.org/10.1016/j.desal.2004.11.065.
[17] S. Venkata Mohan, N. Chandrashekara Rao, K. Krishna Prasad, B.T.V. Madhavi, P. N. Sharma, Treatment of complex chemical wastewater in a sequencing batch reactor (SBR) with an aerobic suspended growth configuration, Process Biochem. 5 (April 2005) 1501–1508, https://doi.org/10.1016/j.procbio.2003.02.001.
[18] V.I. Nezdoyminov, D.V. Zavorotnyi, Vliyanie Vnutrennih Tsirkulyatsionnyh Potokov V Aerotenke-Osvetlitele Na Obrazovanie Podvizhnogo Filtruyshego Vzveshennogo Sloya, December 11-14, Materials of the XI International Scientific and Practical Conference. Technologies of water purification "TECHNOVOD-2018"/South.-Russian State Polytechnic University. (NPI) named after M.I. Platov, Sochi, Krasnaya Polyana, 2018, pp. 207–212. Publisher: LLC "Lik", Novocherkassk, Russia.
[19] D.V. Zavorotniy, Eksperimentalnoe opredelenie parametrov modelirovanie aerotenkov-osvetliteley s zatoplennoi erliftnoi systemoy aeratsyi//Collection of scientific works of GOU VPO LNR, DonGTU 10 (53) (2018) 104–109. C.
[20] V.I. Nezdoyminov, Aerotenk-otstoynik s obnovlyauyshimsya vzveshennom sloem/nezdoyminov V.I., Zavorotniy D.V.//bulletin of donbas national academy of civil engineering and architecture, Eng. sys. Techno. safety 5 (121) (2016) 15–19. C.
[21] V.I. Nezdoyminov, D.V. Zavorotniy, V.S. Rozhkov, Protsessy Osvetlenia Ilovoy Smesi Vo Vzveshennom Sloe V Sooruzheniyah S Erliftnoi Systemoi Aeratsyi, October 05-06, Materials of X - Jubilee International Scientific and Practical Conference. Technologies of water purification "TECHNOVOD-2017"/Yuzhno.-Russian State Polytechnic University. (NPI) named after M.I. Platov, Astrakhan, 2017, pp. 268–272. Publisher: LLC "Lik", Novocherkassk, Russia.
[22] V.I. Nezdoyminov, N.N. Golodenko, D.V. Zavorotny, O.B. Maistrenko, Matematicheskoe Opisanie Gidrodinamicheskih Parametrov Erliftnogo Bioreaktora-Osvetlitelya, Journal Vestnik of Donetsk National University. Series: technical sciences, 2020, pp. 84–96.
[23] V.S. Shevtsov, Influence of Water Temperature on Technological Parameters of Clarifier Operation with Suspended Bed of Activated Sludge. Construction in

Coastal Resort Regions: Materials of X International Scientific-Practical Conference/under the Scientific Editorship of Prof. K.N.Makarov; Ministry of Education and Science of the Russian Federation, Sochi State University; Engineering.-Ecological. Faculty. - Sochi, SGU, 2018, p. 338. c.

[24] M.M. Myrzakhmetov, V.P. Kolpakova, Ochistka hozyastvenno-bytovyh stochnyh vod v osvetlitelyah so vzveshennom sloem osadka. Kyrgyz State Technical University, J. Sci. New Technolo. (4) (2009).

[25] V.P. Kolpakova, Sovershenstvovanie Tehnologii I Tehniki Oshistki Stochnyh Vod S Uchetom Proizvodstvennyh Osobennostei Vostochnogo Kazakhstana. Dis... D. Sc., KazNTU Named after K.I.Satpayev, RK Almaty, 2010. Registration number: 0510RK00947.

[26] V. Kolpakova, K. Ospanov, E. Kuldeyev, D. Andraka, Clarification of biologically treated wastewater in a clarifier with suspended sludge layer, Water 13 (2021) 2486, https://doi.org/10.3390/w13182486.

[27] RD 52.24.468-2005: Suspended solids and total impurities in waters. Method for carrying out measurements of mass concentration by the gravimetric method (Reg. No. KZ.07.00.01182-2015).Available online:https://files.stroyinf.ru/Index2/1/4293837/4293837302.htm (accessed on 8 September 2021).

[28] GOST 31859-2012. Water, Method for Determination of Chemical Oxygen Demand, 2014. Standardinform: Moscow, Russia.

[29] NDP 10.1: 2: 3.131-2016, Method for Determining Biochemical Oxygen Demand after 5 Days of Incubation in Drinking, Nat-Ural and Waste Water Samples by Amperometric Method, ZA O "Rosa, Moscow, Russia, 2016.

[30] GOST 33045-2014, Water. Methods for the Determination of Nitrogen-Containing Substances; Standartinform: Moscow, Russia, 2019.

[31] FR 1.31.2008.04399, Methods for Measuring the Ash Content of Wet Activated Sludge, AKVAROS, Moscow, Russia, 2008.

[32] Methodology for Performing Measurements of Sludge Dose by Volume and Calculation of Sludge Index, FR 1.31.2008.04398. Moscow "AQUAROS", 2008.