Development and simulation of the operation of a two-tier sedimentation tank for urban wastewater treatment

A E Novikov¹, M I Filimonov¹, A E Khadzhidi² and E A Dugin¹

¹ All-Russian Research Institute of Irrigated Agriculture, 9 Timirjaseva Street, Volgograd 400002, Russian Federation
² Kuban State Agrarian University, 13 Kalinina Street, Krasnodar 350044, Russian Federation

E-mail: novikov-ae@mail.ru

Abstract. One of the main reasons for the increase in the ecological tension of aquatic ecosystems remains the discharge into water bodies of domestic wastewater containing toxic substances and pathogenic microorganisms. This is due to the imperfection of water treatment technologies, including due to wear and tear of utility networks and violations in the technological process, accompanied by salvo emissions. Reducing the anthropogenic load on water bodies is possible by retechnologizing various stages of wastewater treatment. The paper describes the design of a sedimentation tank with aeration elements for clarification of urban wastewater, providing an increase in the efficiency of sedimentation of suspended solids. Spraying fine air bubbles contributes to the collision and enlargement of aggregate-unstable elements without the use of coagulants and flocculants. The paper presents a mathematical algorithm for calculating the required deposition surface, taking into account the wastewater flow rate, the nominal diameter of the dispersed phase particles and the required degree of purification. Numerical experiments have shown that for a settlement with a population of 100,000 people, a treatment plant with a standard sedimentation tank is required, the area of which is 130 m². The use of a sedimentation tank with aeration elements in similar conditions allows reducing the required clarification surface to 120.9 m² without reducing the clarification efficiency. It has been proven that the spraying of finely dispersed air bubbles helps to reduce the required settling area of the sump by 8%.

1. Introduction

High rates of global urbanization, combined with rapid population growth, are responsible for the emergence of a shortage of fresh water and an annual increase in the volume of urban wastewater. Many scientists agree that modern water supply and sewerage systems should ensure not only the management of water resources, but also the restoration of their natural potential [1, 2]. The main use of treated wastewater is the agricultural sector of the economy, which annually consumes up to 70% of water resources of the total global water withdrawal [3]. Urban wastewater contains a wide range of chemical elements such as arsenic As, cobalt Co, lead Pb and pathogenic microflora, which have a negative impact on human and animal health. Therefore, the safe use of wastewater in irrigation reclamation is possible only after their preliminary treatment at treatment facilities. Considering the urban sewerage infrastructure, it is generally accepted that it receives household wastewater generated as a result of the population's vital activity, and surface runoff, consisting of rain and melt water. Figure 1 shows the main pollutants found in urban wastewater [4].
Analyzing the data presented, we can conclude that one of the main pollutants is mechanical impurities and biogenic elements in suspension. Sedimentation tanks are widely used for removing suspended solids at treatment facilities. The widespread use of these devices is due to the simplicity of their design, high energy efficiency and long service life. The main disadvantage of sedimentation tanks is the insufficient degree of capturing of finely dispersed impurities in suspension. As a result of many years of research by Chinese scientists, it has been established that the average efficiency of the Chinese wastewater treatment plant is 0.51. The authors note the need to improve existing technologies for urban wastewater treatment [5]. Analysis of the work of domestic treatment facilities showed that the efficiency of removing suspended solids ranges from 0.8 to 0.92, depending on the technologies and equipment used. In their works [6-10], scientists agree on the need to retechnologize existing wastewater treatment processes.

A promising direction for the intensification of sedimentation of suspended solids in sedimentation tanks is considered to be the enlargement of aggregate-unstable mechanical impurities, as a result of which there is an increase in the mass of particles and an increase in the rate of their sedimentation. The described method involves the use of various coagulants and flocculants, the choice of which depends on the properties of the liquid to be purified. [11, 12]. The disadvantage of this method is the need for a reagent facility, as well as operational control within narrow limits of the concentration of the flocculant.

Thus, the aim of the study was to intensify the process of urban wastewater treatment by agglomeration of suspended particles without the use of flocculants.

2. Methods and materials
To improve the processes of urban wastewater treatment, the design of a two-tier sedimentation tank was developed, the diagram of which is shown in Figure 2 [13].

The main element of the two-tier sedimentation tank is a cylindrical reinforced concrete tank with a conical bottom, which provides collection and accumulation of settled sludge. Inside the cylindrical part, sedimentation gutters made of sheets of polymer material are installed. To intensify the separation of suspended solids, the lower walls of the gutters are made inclined with slotted slots.
connecting the working area of the sedimentary gutters with the sludge chamber. From the outer part of the gutters along their entire length, aerators are located, providing fine dispersion of air bubbles.

![Diagram](image)

**Figure 2.** Double deck sump for wastewater treatment:
1 - reinforced concrete tank with conical bottom; 2 - sludge chamber; 3 - sediment gutter; 4 - aerators; 5 – sludge.

The described design provides an increase in the efficiency of the settler due to the coarsening of particles of the dispersed phase.

Determination of the free surface of the settler, necessary for effective wastewater treatment, was carried out by calculation. This method is based on the condition under which the deposition of particles to the bottom of the settling tank occurs when the residence time of the considered particles $\tau_p$ is greater than or equal to the time of their deposition $\tau_{os}$. Taking this condition into account, we write the following expression [14]:

$$\frac{\nu}{\nu_{\text{nom}}} = 1.5 \left( \frac{h}{H} \right)^2 - 0.5 \left( \frac{h}{H} \right)^3,$$

where $\nu$ - sedimentation rate of particles of each fraction, m/s;
$\nu_{\text{nom}}$ - sedimentation rate of particles captured by 100%, m/s;
$h$ - height from which particles of each fraction have time to reach the bottom, m.

The sedimentation rate of particles captured by 100% is characterized by the dependence:

$$\nu_{\text{nom}} = \frac{g d_{\text{nom}}^2 (\rho_{\text{sol}} - \rho_{\text{liq}})}{18 \mu},$$

where $d_{\text{nom}}$ - diameter of particles captured at 100%, m;
$\rho_{\text{sol}}$ - solid phase particle density, kg/m$^3$;
$\rho_{\text{liq}}$ - density of the liquid phase, kg/m$^3$;
$\mu$ - fluid viscosity, Pa·s;
$g$ - acceleration of gravity, 9.81 m/s.

Assuming that suspended particles are evenly distributed in the input stream, then $h/H$ characterizes the fraction of captured particles $\chi$ deposited at a rate $\nu \leq \nu_{\text{nom}}$.

Taking into account the spherical shape of the particles, as well as the laminar deposition mode, we obtain:
\[
\left( \frac{d_i}{d_{i_{\text{nom}}}} \right) = 1.5 \chi^2 - 0.5 \chi^3. 
\]

where \( d_i \) - particle diameter of each fraction, m.

Knowing the density of distribution of particles by fractions \( C \), we determine the local degree of capture:

\[
C_{\text{cap}} = C \cdot \chi. 
\]

Summing up the local degrees of particle capture, we determine the overall degree of cleaning:

\[
\eta = \sum_{i=1}^{n} C_{\text{cap}}. 
\]

Thus, given the required degree of purification \( \chi \), the diameter of particles captured by 100% and the flow rate of the initial suspension \( q \), we determine the required surface of the settler:

\[
F = \frac{q}{u_{\text{nom}}}. 
\]

The described calculation algorithm characterizes standard sedimentation tanks and does not take into account the presence of additional elements, such as aerators.

3. Results and discussion

During the operation of the two-tier sedimentation tank, domestic or industrial wastewater with suspended solids enters the reinforced concrete tank \( I \) and is distributed along the sedimentary troughs \( 3 \). As the flow passes, the sludge fraction under the action of gravitational forces settles along the inclined part of the troughs and slides through the slot holes into the sludge chamber \( 2 \). The continuous movement of the water flow along the sediment troughs is accompanied by air spraying through aerators \( 4 \) installed along the entire length from the outside of the troughs. Finely dispersed air bubbles ensure turbulization of the wastewater flow and contribute to the appearance of additional inertial forces. The combined action of these factors contributes to the direct collision of aggregate-unstable suspended solids, and the enlargement of their size. As a result of gravitational coagulation, small particles are captured by larger fractions, which leads to the maximum penetration of sediment into the sludge chamber. In the sludge chamber, sedimentation of the remaining finely dispersed fraction of suspended solids occurs and, due to the conical shape of the bottom of the reinforced concrete tank, collection and compaction of sediment at the lower point of the settler. After the separation of mechanical impurities, the streams of purified water from the sediment troughs and the sludge chamber are mixed in the outlet collector and fed to the next purification stages.

When calculating the required surface of the sump, we proceeded from the average rate of drainage per inhabitant, which is 350 liters per day. Using the data presented in Figure 1, we took the initial concentration of suspended solids as the total amount of mechanical impurities in the household and drainage waste. Analysis of works devoted to the study of the fractional composition of suspended solids in wastewater, made it possible to establish that the nominal particle diameter of the dispersed phase is 420 \( \mu \text{m} \) [15]. Setting the required degree of purification at the level of 0.95, we will compile a table 1 of initial data for calculating the sedimentation tank of treatment facilities per 100,000 inhabitants.

When calculating the required surface of the proposed sedimentation tank, it is necessary to take into account the aeration coefficient, which characterizes the increase in the efficiency of sedimentation. In classical work on drainage and sewerage [16], the value of the aeration coefficient varies within 1.1-1.15. Known experimental studies [17], which describe the results of wastewater clarification using aeration. According to the data obtained, atomization of finely dispersed air bubbles provides an increase in the efficiency of sedimentation of suspended solids by 8%.

Taking into account the increase in the efficiency of wastewater treatment, we will calculate the required surfaces for the variants of the sedimentation tank of a typical and developed design. The results of mathematical calculations are shown in Figure 3.
Table 1. Initial and reference data for calculating the sedimentation tank.

| Parameter name                          | Designation | Units         | Parameter value |
|-----------------------------------------|-------------|---------------|-----------------|
| Wastewater consumption                  | $q$         | m$^3$/hour    | 1800            |
| Initial concentration of suspended solids | $x_{in}$   | g/l           | 210             |
| Required degree of purification         | $\eta$     | –             | 0.95            |
| Diameter of particles captured at 100%  | $d_{nom}$  | mk            | 420             |
| Solid phase particle density            | $\rho_{sol}$ | kg/m$^3$      | 1050            |
| Density of the liquid phase             | $\rho_{liq}$ | kg/m$^3$      | 1000            |
| Fluid viscosity                         | $\mu$      | Pa/s          | 0.001           |

Figure 3. Comparison of the required surface of sedimentation tanks of typical and developed designs.

4. Conclusion
The volume of generated wastewater can vary in a wide range, which is due to various anthropogenic and natural factors. Using the average value of drainage per person, we calculated the required surface of a standard sump and sump of the proposed design for urban wastewater treatment plants using a numerical experiment, taking into account the effluent output per 100,000 people. It was found that a standard sump with a sedimentation surface of 130 m$^2$ is required to clarify a given volume of wastewater. When using the proposed design, under the same conditions, the required sedimentation surface is 120.9 m$^2$.

Thus, the developed design of the settling tank with aeration elements provides a cleaning efficiency of 95% with a deposition surface of 120.9 m$^2$, which is 8% less than the required area of a standard settling tank.

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