Parameter Calculation Technique for the Waste Treatment Facilities Using Naturally-Aerated Blocks in the Bog Ecosystems

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Abstract. Technique for the domestic wastewater treatment in the small residential areas and oil and gas facilities of the natural and man-made systems including a settling tank for mechanical treatment and a biological pond with peat substrate and bog vegetation for biological treatment has been substantiated. Technique for parameters calculation of the similar natural and man-made systems has been developed. It was proven that effective treatment of wastewater can be performed in Siberia all year round.

1. Introduction
Effective wastewater treatment is one of the key objectives in solving the problem of preservation and restoration of the disturbed environment components. A lot of attention is paid to the solution of this problem, thus, new methods of treatment are being developed, layout of the waste treatment facilities and their integration in the natural and man-made complex [1, 2] are being optimized as well, though, nowadays the last aspect is insufficiently elaborated both from theoretical and practical point of view. As a result, quite expensive waste treatment facilities are being built in Siberia, they don’t always provide a necessary level of wastewater treatment from organic and biogenic substances (probability of emergencies in the work of biological artificially-aerated treatment facilities in severe weather conditions is rather high), while regional natural features which enable natural aeration of the wastewater and reduction of the pollutant concentration using aquatic and bog vegetation are not properly used. Special work is surely carried out in this direction but mostly in the European Union, the USA, also in the European part of the Russian Federation [2]. Similar investigations with regard to Siberian conditions are carried out in Tomsk State University, but, unfortunately, the results obtained are rather empirical and give no way to methodology for design of the waste treatment facilities with naturally-aerated blocks and adsorption of pollutants with hydrophilic vegetation.

Taking this into consideration the investigations concerning the development of methodology for creation of the natural and man-made system intended for nature protection purposes, including treatment facilities integrated in the natural biogeochemical cycle, have been carried out over a period of years in Tomsk Polytechnic University. In particular, a technique (adapted to the conditions in Siberia) for domestic wastewater treatment in the small residential areas and oil and gas facilities in the shallow biological ponds with peat substrate and bog vegetation by means of sorption of pollutants on the peat particles, their adsorption by vegetation and organic-matter degradation was offered earlier [3]. Results of the further stage of investigations, i.e. technique for design of such facilities, are presented below.
2. Domestic Wastewater Treatment Objectives and Constrains to Treatment

Any wastewater treatment technology must be adapted to the chemical composition and treatment conditions. To solve this problem data of ecological monitoring in the territory of Tomsk Oblast were analyzed, as a result, the following conclusions were made. Firstly, domestic wastewater which comes to the treatment facilities of the region contains NO\textsubscript{3}\textsuperscript{-}, NH\textsubscript{4}\textsuperscript{+}, PO\textsubscript{4}\textsuperscript{3-}, Si, Fe, Cu, Zn, Pb, phenols, oil minerals, surface active substances, organic substances in the amount higher than maximum permissible based on the 5-day biochemical oxygen demand test with permanganate and dichromate as the oxidants (table 1). Increased concentration of Si and Fe can be explained by the fact that underground water is high in Si and Fe content (iron is contained both in the water being used and discharges of the facilities for iron removal; silicon comes mainly with domestic water being in use), water contamination during conditioning and transportation of domestic water causes high Pb concentration. High content of organic substances in the wastewater and products of their degradation, nitrogen and phosphorus compounds, are quite regular. Cu concentration (and also Zn and Fe) that is higher than maximum permissible for fisheries streams is commonly found in the underground, river, lake and bog waters of the region, so we can’t associate it with certain anthropogenic factors.

Secondly, as a result of treatment, the content of suspended substances, dissolved HCO\textsubscript{3}\textsuperscript{-}, SO\textsubscript{4}\textsuperscript{2-}, NH\textsubscript{4}\textsuperscript{+}, Fe, Al, Cu, Zn, Pb, phenols, surface active substances, oil minerals, organic substances based on the 5-day biochemical oxygen demand test (BOD\textsubscript{5}) with permanganate (PO) and dichromate (DO) as the oxidants in the wastewater decreases, concentration of PO\textsubscript{4}\textsuperscript{3-} and Si is without considerable change, dry residue and sum of major ions of \(\Sigma\text{pi}, \text{Na}^+, \text{K}^+, \text{Ca}^{2+}, \text{Mg}^{2+}, \text{Cl}^-, \text{NO}_2^-, \text{NO}_3^-, \text{Cl}^-\) increase. Maximum permissible concentration (MPC) of \(\Sigma\text{pi}, \text{Na}^+, \text{NO}_2^-, \text{NO}_3^-, \text{PO}_4^3-, \text{Si}, \text{Fe}, \text{Cu}, \text{phenols}, \text{oil minerals}, \text{organic substances based on BOD}_5, \text{PV}, \text{DV}\) is exceeded on the average. In case of Na\textsuperscript{+} it can be explained by the excess decontamination of wastewater with sodium hypochlorite, in case of \(\Sigma\text{pi}, \text{NO}_2^-, \text{NH}_4^+, \text{PO}_4^3-\) (and other substances with lower concentration than MPC) exceeded maximum permissible concentration is caused by the inefficient removal of organic substance degradation products from wastewater, it suggests that advanced waste treatment is necessary. In practice silicon is not removed from wastewater, its concentration is almost the same before and after treatment of wastewater and underground waters from the aquifers in use. Removal of oil minerals, surface active substances, organic substances based on BOD\textsubscript{5}, PV, DV is rather effective (degree of treatment is higher than 30…50\%), though, it doesn’t allow to rich water quality target.

Thirdly, metal concentration in the wastewater tends to decrease in the process of precipitation of suspended substances. This indicates the significance of the given stage of wastewater treatment. Fourthly, many substances in the domestic wastewater are components which are necessary for forest community development in taiga zone of Siberia, particularly in the area of domed oligotrophic bog development [4]. In particular, NO\textsubscript{3}\textsuperscript{-}, PO\textsubscript{4}\textsuperscript{3-} and easily oxidizable organic substances (based on BOD\textsubscript{5}) can be referred to such substances for the wetlands of Tomsk Oblast. Fifthly, construction of expensive artificially-aerated treatment facilities operated by qualified people in the administrative areas of the Siberian and Urals Federal Districts which are characterized by the bogginess of the territory, severe climate and vast distance from cities doesn’t provide the required quality of wastewater treatment.

Thus, nowadays money is spent over balance (in relation to the results achieved) on domestic wastewater treatment from substances which are in short supply in the wetlands, the factor that affects development of the forest communities in the vast territory of Tomsk Oblast and other regions. Therefore, it is reasonable and even necessary to consider possibility of bog feeding with the treated wastewater or the use of bogs or their zones for treatment of the domestic and storm wastewater from the small residential areas and rotation villages. Considering restrictions of the environmental legislation it enables to improve forestry in Western Siberia in response to the peat accumulation increase by 1 mm per year and to reduce costs on housing and utilities sector without environmental damage. Key objectives for the wastewater treatment in such natural and man-made systems are the following: 1) precipitation of the suspended substances as an important factor for reduction of toxic trace substance concentration (Pb, Zn, etc.); 2) reduction of concentration of organic and biogenic...
substances as they are assimilated by bog vegetation and absorbed by peat. Giving due consideration to the regulatory requirements a typical scheme for domestic wastewater treatment involves mechanical treatment in a settling tank and biological treatment in a biological pond with peat substrate and bog vegetation.

### Table 1. Average values of hydrochemical and physicochemical parameters of domestic wastewater and storm water run-offs in the territory of Tomsk Oblast before and after treatment.

| Parameter       | Units of measure | Wastewater before and without treatment | Wastewater after treatment | Storm wastewater | MPC_{th} | MPC_{db} |
|-----------------|------------------|----------------------------------------|---------------------------|-----------------|----------|----------|
|                 |                  | A | N | A | N | A | N |           |          |
| \( \Sigma_{pi} \) | mg/dm³           | 808.2 | 12 | 1179.7 | 17 | - | - | 1000.0   |          |
| NO\textsubscript{3} | mg/dm³           | 0.247 | 82 | 1.178 | 139 | 0.775 | 35 | 0.080 | 3.300 |
| NH\textsubscript{4} | mg/dm³           | 45.537 | 82 | 36.068 | 139 | 5.684 | 34 | 0.500 | 1.930 |
| BOD\textsubscript{5} | mgO/dm³        | 175.63 | 28 | 64.55 | 90 | 31.12 | 35 | 2.00 | 2.00 |
| DO              | mgO/dm³         | 278.10 | 53 | 164.80 | 102 | 81.46 | 35 | - | 15.00 |
| Phenols         | mg/dm³          | 0.128 | 77 | 0.013 | 136 | 0.008 | 23 | 0.001 | 0.001 |
| Oil minerals    | mg/dm³          | 1.579 | 65 | 0.232 | 119 | 0.388 | 32 | 0.050 | 0.300 |

Note: \( A \) – average value, \( N \) – number of samples, \( \Sigma_{pi} \) – sum of major ions; BOD\textsubscript{5} – 5-day biochemical oxygen demand; DO – dichromate oxibility.

### 3. Calculation of Parameters of the Mechanical Treatment Block

The main mechanical treatment is carried out in a settling tank, where suspended substances are precipitated. Types of the settling tank are chosen according to engineering analyses (mainly depending on the land topography and peat bed, water inflow and its distribution in the area, the presence of confining layer and its power): an excavated pond with bunding; an excavated pond with earth-fill dam and bunding; a pond with bunding and a dam. The bottom, bunding and the pond dam should be constructed with low permeability soils or using waterproofing [3].

Parameter calculation of the mechanical treatment unit is performed according to [5]. Total flow of wastewater which gets into the wastewater treatment plant (WTP) is determined by the customer (water consumer) depending on the population size (number of employees at the site), current standards for wastewater disposal and irregularity of wastewater inflow. Amount of water pollutants per one resident \( m_{or} \) for determination of their concentration in the domestic wastewater of the treatment facilities being designed is taken according to [5], and concentration of pollutants \( S \) (g/m\textsuperscript{3}) is calculated by the following formula:

\[
S = m_{or} \cdot N_p / q_m,
\]

where \( N_p \) is a number of residents, people; \( q_m \) is a calculated annual average wastewater flow rate with account for irregularity of inflow, m\textsuperscript{3}/day; \( m_{or} \) – amount of water pollutants per one resident.

Throughput of a single settling basin \( q_{set} \) (m\textsuperscript{3}/hr) is estimated according to the predetermined dimensions of the facility and the required effect of wastewater clarification using a formula for horizontal-flow settling basin:

\[
q_{set} = 3.6 \cdot K_{set} \cdot L_{set} \cdot B_{set} (u_0 - v_{th}),
\]

where \( K_{set} \) is the factor of utilization of the flow part of the settling basin; \( L_{set} \) is the total length of the settling basin, m; \( B_{set} \) is the width of the horizontal-flow settling basin determined by correlation \( B_{set} \approx (2 \ldots 5) \cdot H_{set} \), where \( H_{set} \) is the depth of the flow part (values \( L_{set} \) and \( H_{set} \) are determined by way of selection corresponding to the predetermined clarification effect and bottom slope of the settling basin); \( v_{th} \) is the turbulence component (mm/s) of the flow velocity \( v_o \) which is determined by the maximum daily wastewater flow and the average section area. Hydraulic coarseness of particles \( u_0 \) is determined by formula:

\[
\text{Units of measure: } mg/dm³, \text{ water consumer: } m_{or}, \text{ number of residents: } N_p, \text{ water consumer: } q_m, \text{ annual average average wastewater flow rate: } S \text{ (g/m³)}, \text{ factor of utilization: } K_{set}, \text{ total length of the settling basin: } L_{set}, \text{ width of the horizontal-flow settling basin: } B_{set}, \text{ factor of utilization of the flow part of the settling basin: } 3.6, \text{ depth of the flow part: } H_{set}, \text{ turbulence component of the flow velocity: } v_{th}, \text{ maximum daily wastewater flow: } v_o, \text{ hydraulic coarseness of particles: } u_0.\]
4. Calculation of Parameters for the Biological Treatment Block

Biological treatment is performed annually in the block which is basically a bog (or a part of it) and similar in function to a shallow biologic pond with hydrophilic vegetation. The main difference of such a block (hereafter biologic pond with peat substrate BPPS) from an ordinary shallow pond is in using regional bog vegetation and additional wastewater treatment by sorption of pollutants on the particles of the peat substrate. Wastewater from the settling basin gets through a discharge sluice into a biologic pond all year round. Design parameters of the biologic pond with peat substrate are calculated considering requirements [5] for organic waste content reduction based on BOD\textsubscript{tot} determining minimum permissible parameters. The latter can be increased as a result of calculation of the degree of treatment from other substances which are contained in wastewater. Thereafter, there are two stages of parameter determination of BPPS, calculation algorithm is applied as follows. Firstly, condition specified in [5] is verified, according to it wastewater being treated in the naturally-aerated biological ponds mustn’t have BOD\textsubscript{tot} higher than 200mg/l. If this condition is not satisfied additional sections of settling tanks are designed. The time of stay of wastewater \( t_{\text{lag}} \) (days) in the naturally-aerated pond is determined from the formula:

\[
 t_{\text{lag}} = \frac{1}{k \cdot K_{\text{lag}}} \sum_{1}^{N-1} \frac{L_{\text{en}}}{L_{\text{ex}}} + \frac{1}{k' \cdot K'_{\text{lag}}} \frac{L_{\text{en}} - L_{\text{fin}}}{L'_{\text{en}} - L'_{\text{fin}}},
\]

where \( N \) is the number of successive stages of a pond; \( K_{\text{lag}} \) is the factor of utilization by volume of each stage of the pond; \( K'_{\text{lag}} \) is the same, but for the last stage of the pond; \( L_{\text{en}} \) is the BOD\textsubscript{tot} value of the wastewater coming into a given stage of the pond; \( L'_{\text{en}} \) is the same, but for the last stage of the pond; \( L_{\text{ex}} \) is the BOD\textsubscript{tot} value of the wastewater exiting from the given stage of the pond; \( L'_{\text{ex}} \) is the same, but for the last stage of the pond; \( L_{\text{fin}} \) is the residual BOD\textsubscript{tot} value determined by the processes inside the pond and taken 2 mg/dm\(^3\); \( k \) is the constant of the oxygen consumption, day\(^{-1}\); \( k' = -0.07 \) day\(^{-1}\) at a water temperature 20°C [5]. Minimal total area of a biological pond with peat substrate \( F_{\text{lag}} \) (m\(^2\)) is determined from the formula:

\[
 F_{\text{lag}} = q_{w} \cdot C_{a} \cdot \frac{(L_{\text{en}} - L_{\text{ex}})}{K_{\text{lag}}} \cdot \frac{(C_{a} - C_{\text{ex}})}{r_{a}},
\]

where \( q_{w} \) is the flow rate of waste water, m\(^3\)/day; \( C_{a} \) is solubility of oxygen (natural aeration); \( C_{\text{ex}} \) is the concentration of oxygen that shall be maintained in water exiting the pond, mg/L; \( r_{a} \) is the value of atmospheric aeration in shortage of oxygen equaling 1 taken at 3...4 g/(m\(^2\)·day). After this the depth of a pond \( H_{\text{lag}} \) (m) is determined from a formula (1), the working depth of a pond mustn’ t exceed: with \( L_{\text{en}} \) above 100 mg/dm\(^3\) – 0.5 m, with \( L_{\text{en}} \) up to 100 mg/dm\(^3\) – 1 m; for the deep treatment ponds with \( L_{\text{en}} \) from 20 to 40 mg/dm\(^3\) – 2 m, with \( L_{\text{en}} \) up to 20 mg/dm\(^3\) – 3 m [5]

\[
 H_{\text{lag}} = K_{\text{lag}} \cdot \frac{(C_{a} - C_{\text{ex}})}{r_{a} \cdot t_{\text{lag}} \cdot C_{a}} \cdot (L_{\text{en}} - L_{\text{ex}}).
\]
values is used to determine the height of the bunding from inorganic soil around a selected part of the bog.

A channeling facility, which forms nonlinear flow of wastewater (r in length) with limited meandering for the treatment duration increase, is constructed inside a biological pond using inorganic soil, sludge from the settling basin, tree vegetation remained in the area of biological pond during construction [3].

At the second stage permissible concentration of organic matter based on BOD\(_5\) and other substances is determined from the formulas:

\[
C_{\text{w,lim}} \leq C_b \left( \lambda \cdot f(C) - \lambda + 1 \right) + n \cdot f(C) \cdot Z_{\alpha} \cdot \sigma \cdot \frac{2}{M},
\]

\[
f(C) = \exp \left( k_c \cdot r^2 / 2 \cdot \left( D - \frac{q_w}{\varphi \cdot 0.5 \cdot h_{ap}} \right) \right),
\]

where \(C_{\text{w,lim}}\) is a permissible substance concentration in the peat water in the control section, which is situated at a distance \(r\) from wastewater discharge; \(\lambda\) is a reciprocal dilution of the wastewater; \(Z_{\alpha}\) is a critical value of Student’s coefficient at significance level \(\alpha=0.05\); \(M\) is a series length of the hydrochemical observations at the bog under study or similar bogs where background substance concentration is calculated \(C_b\); \(\sigma\) is a mean square deviation of the substance concentration; \(k_c\) is a self-purification coefficient; \(D\) is a dispersion coefficient, m\(^2\)/s; \(h_{ap}\) is an active layer of bog, m; \(\varphi\) is a sector angle of distribution of impurities; \(C_b\) is a background substance concentration in the peat water for the edge or homogeneous site of the main part of the bog where influents get; \(q_w\) is in m\(^3\)/s.

Equations (2, 3) are proved in [6]. If \(C_{\text{w,lim}}\) is higher that permissible value (maximum possible or background depending on their relation and prevailing sources of substance influent by the method of hydrochemical balance analysis [6], value \(r\) is increased in formula (3) and, consequently, area of BPPS expands till the required result is obtained. It must be mentioned that relation between values \(F_{lag}\) and \(r\) is linear only when \(r\) is the length of BPPS.

5. Waste Management

Treated effluent is discharged from biological ponds in the water disposal system, where it is disinfecting using a dosing tank with disinfectant solution or by means of periodic back filling of BPPS adjacent to the treated effluent discharge with lime. After disinfection the treated effluent is fed into a body of water. Sludge is removed from the settling pond in the frost-free period of the year (1...2 times) if and when it is accumulated. Sludge is moved inside the biological pond to the channeling facility. Sludge can be hauled away to the recultivated sites of the disturbed lands and waste landfills. Sludge is disinfected by mixing with quicklime. Liming to the sludge is determined in the process of treatment facility design on the basis of engineering research analysis. Sludge application rate \(C_{\text{ws}}\) is determined by the formula:

\[
C_{\text{ws}} = 2.4 \cdot (\text{MPC}_s - C_{bp}),
\]

where \(C_{bp}\) is an initial substance concentration in the peat before sludge application, mg/kg; \(\text{MPC}_s\) is maximum permissible substance concentration in peat (soil), mg/kg. If \(\text{MPC}_s\) is not available background concentration in the peat of the bog under study or similar bogs is used. Maximum dose is limited by the total nitrogen content which is applied with sludge and mustn’t exceed 300 kg/ha a year.

6. Wastewater Treatment Plant Operation Conditions during Wintertime

A typical drawback of the shallow-water-type biological ponds is that wastewater treatment is grown worse or stops in winter when their surface is totally or partly frozen and aquatic vegetation dies. But as far as biological pond with peat substrate is concerned, this problem is solved as a result of sorption of substances by peat and peat microbiocenosis. To confirm this thesis samples of bog water were taken in winter (20.02.2013) at different distances from the place where domestic wastewater of the
housing and utilities sector of the village Melnikovo (regional centre of Tomsk Oblast) is discharged into the Ob bog. Their chemical and microbiological content was determined (table 2).

Table 2. Chemical and microbiological content of the polluted peat water of the active layer of the peat deposit of the Ob bog in the area affected by wastewater discharge in the village Melnikovo as of 20.02.2013.

| Parameter                  | Units of measure | Distance from the dry land with wastewater discharge |
|----------------------------|------------------|-----------------------------------------------------|
| NO$_3^-$                  | mg/dm$^3$        | 0.012 0.002                                         |
| NH$_4^+$                  | mg/dm$^3$        | 35.00 2.34                                         |
| PO$_4^{3-}$               | mg/dm$^3$        | 18.200 0.084                                       |
| BOD$_5$                   | mgO$_2$/dm$^3$   | 6.78 2.40                                         |
| Mineral oils              | mg/dm$^3$        | 0.400 0.029                                       |
| Psychrophilic saprophyte  | kl/ml            | 10130 540                                          |
| Nitrogen-fixing           | kl/ml            | 51500 31200                                       |
| Ammonifying               | kl/ml            | 1000 100                                           |
| Oil-degrading             | kl/ml            | 1850 510                                          |

Analysis of the obtained data suggests a significant microbiological activity of the peat water under study during wintertime and makes it possible to explain this activity by the significant reduction NH$_4^+$, PO$_4^{3-}$, BOD$_5$ concentration. Therefore, the main function of the biological pond, i.e. removal of organic and biogenic substances from wastewater, is successfully performed even in winter.

6. Conclusion

Technique for calculation of the natural and man-made system used for domestic wastewater treatment of the small residential areas and consisting of the blocks for mechanical treatment in the settling tank and biological treatment in the biological pond has been offered. Biological pond is a part of the bog with peat (peat substrate which is formed as a result of wastewater – initial peat interaction) and bog vegetation. The use of the technique and method of BPPS design makes it possible to treat effectively domestic wastewater at considerable cost cutting and stability of operation. Direction of the further investigations concerning substantiation of the similar facility constructions involves development of technologies of transformation of the peat substrate and wastewater sludge from the settling tanks into substrate for forest melioration of the wetlands.

7. References

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