

Conditions of contaminant distribution in the wetland water of Western Siberia (the Russian Federation)

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Abstract: The models of pollutants' distribution in the wetland waters of Western Siberia (Tomsk Oblast, Russia) have been considered. The models' application allows describing the observed changes in the chemical composition of active layer of wetland waters with satisfactory accuracy. With these models, the most significant impact of sewage discharge on the local wetland water composition is observed in wetland edge area of up to 150–300 m in width. Even in this area it is possible to minimize the impact of sewage discharge on the wetlands provided the concentration in sewage water is 1.14–1.3 time more than the background concentration.

1. Introduction

The lowlands of the Ob River basin are characterized by high bogginess, which is 30 % from catchment area of the river or even more in some regions. Besides, at present, further wetland formation is in progress, particularly, in the subzones of the south and middle Taiga (the Ob River's middle course), where a number of authors pointed out the mean rate of vertical growth in the peat deposit thickness of 0.39–0.80 mm/year at maximum to 2.62 mm/year, whereas the wetland area increases by about 100 km²/year [1, 2]. Besides, in this area a major portion of the Russian Federation's oil and gas production is located [4]. It necessitates the adaptation of regional economic activity to the high bogginess, and, consequently, conditions the relevance of the research in the wetland ecosystem of Siberia, the key properties of which are connected with the excessive humidity (the thickness in the research area is 3–5 m, sometimes – up to 11 m). In the present paper, the research results on one of the aspects of the problem, namely, ways and conditions of pollutant distribution in wetland water have been considered. The research performed with participation of workers of Tomsk Polytechnic University (the Russian Federation, Tomsk) within 1997–2014 was taken as the initial data [3, 4].

2. Materials and Methods

The following research sites were chosen: 1) the north-eastern part of the Vasugan bog located in the watershed area of the Iksha and Bakchar Rivers (tributaries of the Chaya River – the Ob River's left tributary); 2) the oligotrophic bog located in the suburb of Strezhevoy (Strezhevoy bog); 3) the



eutrophic Obskoye fen near the Mel'nikovo settlement (Figure 1). The choice of wetlands is determined by the following factors.

The Vasugan bog is one of the largest bogs in the world. According to the different estimates, it has an approximate area ranging from 53.000 to 55.000 km² [1, 3]. The research area is located in the north-eastern part of the wetland and corresponds to the drainage basin of the Klutch River (an element of the Klutch, the Bakchar, the Chaya and the Ob Rivers as well as the Kara Sea) and is characterized by the predominance of the oligotrophic ridge-hollow complexes, sphagnous-pine-shrubs, sphagnous-sedge and sphagnous-sedge-cottongrass, pine-sphagnous-shrubs and hummock-ridge-lake bog ecosystems [3]. In general, the research area is distinguished by the following average values: the peat deposit thickness is 1.95 m, peat decay degree – 22 %, peat ash content – 6 %, peat moisture – 90.1 %. The Strezhevoy bog is oligotrophic and located within the subzone of the middle Taiga on the right bank of the Ob River basin. The peat deposit's average thickness in the research pine-sphagnous-shrub area is 1.75 m; average values of peat decay degree – 24 %, ash content – 4 %, moisture – 90.0 %. The Obskoye fen is of the eutrophic type and covers the left bank of the River Ob valley, a belt from 1.5 to 7 km in width and 104 km in length. Peat deposits in the lowland have the average thickness of 3.2 m. The research area is located near Mel'nikovo settlement and characterized by the average values: peat ash content is 28.7 %, peat decay degree – 34 %; moisture – 83.7 % [5].

The research in wetland peat deposit structure includes investigation of an active layer that demonstrates a transition layer from the peat deposit to the vegetation surface or dense root matting with intense water exchange. Peat deposits are a natural layering of definite peat types from the surface to the mineral wetland bottom. The active layer's thickness in the Vasugan and Strezhevoy bogs is 0.32 m and in the Obskoye fen is 0.52 m thick [6]. The Strezhevoy bog serves as a sink for commercial waste water (after the Strezhevoy system's iron removal plant for the clean ground water supply). The Obskoye fen is a sink for the domestic waste water of the Mel'nikovo settlement. At present, the Vasugan bog's research area is not exposed to apparent anthropogenic effect, but in the future it can be used for settled iron ore production and sewage disposal formed in the production process [7]. According to K.Ye. Ivanov [6]: 1) the motion of wetland waters mostly occurs within the peat deposit's upper active layer h_{al} (the usual thickness is 0.2–0.6 m; relatively high values of filtration coefficient and presence of oxygen are observed in the upper layer 0.2–0.5 m. The exchange processes can, certainly, take place, but their scale is insignificant in comparison with those in the upper layer. Besides, within the bog one can distinguish the sites with different transferring properties

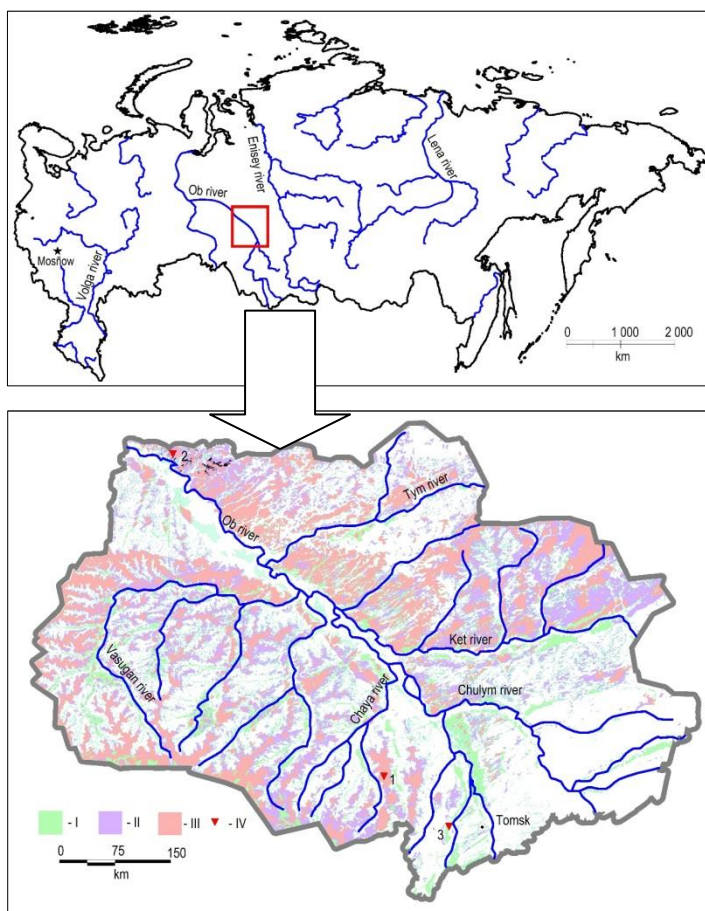


Figure 1. Map of the research areas: I – eutrophic swamps; II – mesotrophic swamps; III – oligotrophic bogs; IV – the research bog areas: 1 – the Vasugan bog; 2 – the Strezhevoy bog; 3 – the Obskoye fen.

not only throughout the whole thickness, but also in the upper layer); 2) the wetland water table gradient J_{bw} approximately coincides with that of the wetland surface J_{bs} ; 3) the inner wetland ecosystems are characterized by relatively constant magnitudes of surface gradients and permeability coefficients in the active layer k_f . On the whole, in terms of changes in water exchange intensity, the flow intensity of substances dissolved in wetland waters decreases from the surface to the bottom with its peak within the active layer.

Thus, the analysis of field observations on polluted wetlands in Western Siberia as well as the results of geo-migration modeling of peat deposit thickness have shown that: 1) short-term inflow of waste water with the total dissolved substances (TDS) of 7211.8 mg/dm³ does not exert a significant impact on ion composition of wetland water limited, mostly, by the active layer; 2) a consequence of the continuous waste water discharge is the more significant change in water composition, the highest pollution being confined to the upper layer of up to 0.5–1.0 m in thickness [4]. In this regard the two alternate solutions of the steady-state plane diffusion equation are used to model the distribution of pollutants in wetland waters. In the first case, the diffusion equation's numerical solution is computed in rectangular coordinates under the assumption of primary substance distribution due to the advection component in longitudinal direction of the wetland (waste – wetland) water flow and diffusive one – in transverse direction [4, 8]:

$$V \frac{\partial C}{\partial x} = D \frac{\partial^2 C}{\partial y^2} + f(C) \quad (1)$$

$$V = k_f J_{bw} \quad (2)$$

$$D = D_m + k_D V \quad (3)$$

where C is the average value of hydrochemical indicator (concentration of the studied substance) in the active layer of peat deposit; x and y are streamwise and crosswise spatial coordinates; V is the velocity of the wetland water flow (if there is an inflow of waste water as well as surface and ground waters from the adjacent dry slopes, the resultant velocity of waste-bog water is calculated for each control point x as an weighted average of the wetland water flow's square and the section's water inflow $[x-1; x]$ under the condition of initial mixing of the water inflow from dry slopes, wetland, and waste waters); D is the hydrodispersion coefficient (it is roughly taken as equal to the coefficient of longitudinal hydrodispersion); D_m is the coefficient of molecular diffusion; k_D is the dispersion coefficient; $f(C)$ is the function of substance inflow and transformation in wetland waters.

Typically, in hydrochemical modeling based on the hydrodynamic approach, the function $f(C)$ has the following forms:

$$f(C) = k_C (C_e^\alpha - C^\beta) \quad (4)$$

$$f(C) = k_C (C_e - C) \quad (5)$$

$$f(C) = k_C C^\beta, \quad (6)$$

$$f(C) = k_C C \quad (7)$$

$$f(C) = 0 \quad (8)$$

$$f(C) = a_0 + a_1 x + a_2 x^2 + \dots, \quad (9)$$

where k_C is the constant of the chemical reaction; C_{eq} is the substance concentration in the solution corresponding to the local equilibrium in "water – organic substance – gas – rock" system; α and β are the coefficients conditionally corresponding to the stoichiometric coefficient in the chemical reaction occurring in the wetland waters and significantly defining the rate of substance concentration

in the water; a_0, a_1, a_2, \dots are the coefficients defined by the least square method by the known values x and the difference between measured and calculated values of the studied hydrochemical indicator at $f(C)=0$. To solve the equation (1), the A. V. Karashev's technique is used [8] based on the finite-difference approach (10) without transporting through the stream borders and the ratio of computation cell dimensions (11):

$$C_{x+1,y} = 0.5(C_{x,y+1} + C_{x,y-1}) + f(C_{x,y})\Delta x / V \quad (10)$$

$$\Delta x = V \Delta y^2 / (2D) \quad (11)$$

where $C_{x,y}$ is the substance concentration in a cell with coordinates x and y ; Δx and Δy are the increments along x and y . The second alternate allows an analytical solution of the diffusion equation in the cylindrical coordinates in the peat deposit active layer for the function $f(C)$ defined by the equation (7):

$$C_{\max} = C_w \exp\left(-k_C r^2 / (2(D - q_w / \varphi h_*))\right) \quad (12)$$

where C_{\max} is the maximum substance concentration in the wetland waters in a control point; C_w is the substance concentration in waste waters; r is the distance from the inflow source to a control point; φ is the substance distribution sector angle; q_w is the sewage flow rate; h_* is a half of the peat deposit active layer thickness. The active layer's thickness and other hydrologic characteristics of wetlands are estimated according to the observation data [6]. When applying the second solution, the coefficient k_C is defined by a selection with the help of the golden section technique (like other coefficients in the formulas (4–9)) and back calculation from (12) according to the observation data with the subsequent determination of dependence of k_C on the distance to sewage discharge point or wetland boundary. To check the accuracy of calculation, the Nash–Sutcliffe coefficient C_E is used [9] for $C_E > 0.5$.

3. Results and Discussion

According to the O. A. Alyokin's classification [10], due to the absence of any direct anthropogenic impact, the wetland waters of research region are generally stated as fresh waters including: sphagnum bogs with very low mineralization as well as fens with medium and sometimes high mineralization (Table 1). On average, local wetland waters are $\text{HCO}_3^-/\text{Ca}^{2+}$ according to their chemical composition, in all cases they contain high concentrations of organic substances and some by-products (for example, ammonium ions), as well as a number of metals including iron and manganese. In terms of pH value, waters of sphagnum bogs are acidic on average, but the waters of fens are weakly acidic [1, 3]. The observation data have shown that in natural conditions sufficient differences in the spatial distribution of dissolved substance concentrations can be observed in the wetland waters even in the adjacent areas of the same wetland. This is explained by the discrete character of substance distribution over the bog territory, the conditions of the wetland and ground water interaction, and the peat deposit properties.

The influence of inner hydrodynamic and geochemical conditions is observed in the polluted wetland areas. In addition, the influence noticeably varies during the year. This is defined by the changes in the peat filtration properties and intensity of biochemical processes at air temperature below zero. A general tendency to decrease in TDS is noticeable in polluted wetland waters when moving farther from a sewage discharge point. According to the calculations performed, this tendency is satisfactorily described by the diffusion plane equation. To calculate the transformations of polluted wetland waters, both the numerical and analytical solutions are applicable for the diffusion equation ($C_E > 0.5$), but the analytical solution are often easier to use. Therefore, the equation (12) can be used for the evaluation of dissolved salt migration in the polluted wetland water in terms of TDS values as well as the substances discharged in significant amounts into wetlands with the relatively homogeneous filtration properties of peat deposits. The numerical solution is more appropriate for

calculating and predicting the migration of dissolved substances for wetland waters in long wetland areas, for which two or more wetland microlandscapes are typical.

Table 1. Wetland waters' average values (A) of hydrochemical indicators and errors of their determination (δ) within 2000–2014.

Indicator	Units	Vasugan bog, $N=41-57$		Strezhevoy bog, $N=8$		Obskoye fen, $N=8-21$	
		A	δ	A	δ	A	δ
pH	pH units	4.78	0.17	5.75	0.25	7.41	0.08
TDS ²	mg dm ⁻³	58.5	10.8	65.8	14.0	1105.6	81.0
NH ₄ ⁺	mg dm ⁻³	5.18	0.42	2.11	0.55	29.96	8.07
Fe	mg dm ⁻³	3.16	0.58	2.28	1.05	29.16	13.48
COD	mgO dm ⁻³	191.0	21.2	112.3	17.2	340.3	101.4
Oil hydrocarbons	mg dm ⁻³	0.248	0.083	0.028	0.015	0.325	0.162

Note: ¹ error of the arithmetic average is defined by the formula: $\delta = \sigma \cdot N^{-0.5}$, where σ is the mean square deviation; N is the number of samples; ² total dissolved substances (TDS); the value is calculated as a sum of principle ions (Ca²⁺, Mg²⁺, Na⁺, K⁺, HCO₃⁻, SO₄²⁻, Cl⁻); the techniques for determination of chemical composition are presented by Ekstein, Savichev, Pasechnik [3]); COD – chemical oxygen demand

The analysis of the field observation data on disturbed wetlands and the results of the sewage discharge modeling at the wetland boundary show that increase in dissolved substances' concentrations as compared to the geochemical background is associated mainly with the zone of 150 to 300 m. In the absences of anthropogenic impact in Western Siberia, such areas are usually referred to as the transition zone between a wetland and non-wetland area. In this case, the groundwater inflows with a significant dissolved salt content and an interaction between acidic wetland waters and mineral particles play a major role in the geochemical condition's development. Hence, the observed effect of anthropogenic activity in the research area has not resulted in sufficient changes in the large wetland hydrochemical balance. On the other hand, the additional (continuous) flow of dissolved salts in waste waters can result in shifting the existing phytocenosis towards increase in peat formation in the inner wetland ecosystems. As a result, fens are being formed in the place of upper bogs [4] with an elevated concentration of dissolved salts.

The latter circumstance defines the necessity for the evaluation of acceptable pollutant absorption into wetland water in which no statistically significant changes in the wetland ecosystem are observed. For this purpose it is recommended ($C_{w,lim}$) to define the acceptable pollutant concentration in waste water, which is based on the comparison of two samples of volume N in the conditionally background (C_b) and disturbed (C_x) states. C_x is determined by the formula (13), where the error δ of determining C_b – by the formula (15):

$$C_x = C_b + f(C)(C_w - C_b)/k_n, \quad (13)$$

$$k_n = (C_w - C_b)/(C_{max} - C_b), \quad (14)$$

where k_n is the multiplicity of dilution (an indicator of how many times the substance concentration decreased in waste waters in the research area); C_w is the substance concentration in waste waters. Supposing that values C_b and C_x are distributed in terms of Gauss's law and dispersions σ_b^2 and σ_x^2 are known to be equal to ($\sigma^2 = \sigma_b^2 = \sigma_x^2$), it is possible to use the Student test in the form:

$$Z = |C_x - C_b| / (\sigma \cdot \sqrt{2/N}). \quad (15)$$

Then, taking into account (13, 14), at the specified critical value Z_α , the assumption (15) for $C_{w,lim}$ can be formulated in the form:

$$C_{w,lim} \leq C_b (k_n/f(C) - k_n + 1) + (k_n/f(C)) Z_\alpha \sigma \sqrt{2/N}. \quad (16)$$

Taking into account calculations of the equations (1–12) this relation amounts to 1.3–6.4 for Tomsk Oblast at the average value 3.0 [16]. The models of dissolved salts distribution were developed for the undisturbed and polluted wetland waters of Western Siberia based on the numerical and analytical solutions of the diffusion equation on a plane. Their application allowed us to describe the observed changes in TDS and other indicators in active layer of wetland water with different anthropogenic load with satisfactory accuracy.

4. Conclusion

The analysis of observation data and modeling results showed that the most significant impact of sewage discharge on the wetland water's chemical composition is observed at the wetland edge, up to 150–300 m in width. In the given distance from the wetland boundary, there occurs a sufficient (usually several times) decrease in dissolved salt concentrations in the wetland waters. The approach to defining the admissible concentration of pollutants in the waste waters $C_{w,lim}$ is considered on the basis of comparing two samples in the conditionally background and disturbed states with the use of the Student test. Its study shows that even in the zone of the waste water impact (up to 150–300 m in width) it is possible to minimize the adverse effects on the wetland, if the concentration of pollutants in waste water is 1.14–1.3 time more than their background concentrations in wetland waters.

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