Water quality and ecology of water bodies in urban territories: St Petersburg as a case study

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Abstract The ecological state of small water bodies located in large cities is the best indicator of the degree of environmental pollution within urban territories. This paper presents data and results on the ecological state of the water system of Lake Lakhtinsky Razliv and its drainage basin located in the northwestern part of St. Petersburg, Russia. The research has evaluated the critical state of the urban water bodies which are regarded as being in stages of ecological regress. The water bodies intercept, transform and accumulate in their bottom sediments the anthropogenically-derived pollutants coming in from the upper part of the drainage system. However it is considered that the water bodies still have not totally lost their possibility for self- purification.

INTRODUCTION

There are 106 water bodies with a water surface area of more than 1 ha in the St Petersburg region with a total area equal to 21 km^2. Most have an artificial origin: ponds in parks, reservoirs on small rivers and water-filled sandpits. The largest inland water body, Lake Sestroretzky Razliv with a surface area of 10 km^2, is a reservoir constructed on the River Sestra in 1723 for the needs of the armoury. The largest natural lakes of the city, the Suzdalskie Lakes, have a glacial origin (Fig. 1). The water bodies are shallow with the mean depth of the deepest lake (Verkhnee Suzdalskoe) being only 5.5 m. The main sources of replenishment for these large water bodies are direct overland rainfall-runoff and precipitation. The coefficient of water exchange varies from 0.03 to 150.

The disturbance of the hydrological regime of inland water bodies within the urban territory is closely connected with their urbanization. The changes that have taken place in morphometry and hydrographic characteristics of both rivers and watersheds have lead to disturbance of lake level regime and inflow conditions. The most striking influence of urbanization is reflected in the water quality of these lakes. Only 2% of the city's lakes can be considered as being conditionally "clean" and most (80%) are polluted to some extent. The endemic pollution of Lake Sestroretzky Razliv is particularly disturbing given that it is used as the source of drinking water for one of the St Petersburg regions. The concentration of heavy metals and oil in the bottom sediments of the water bodies has been used as a reliable and stable indicator of the technogenic pollution. The bottom sediment of nearly all the St Petersburg water bodies can be classified as extremely polluted in terms of Ni, Cd and oil parameters.

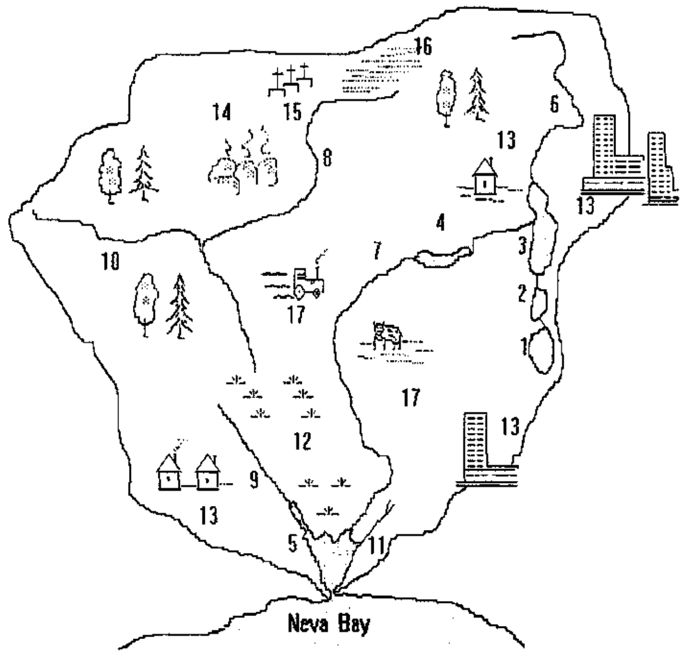

Fig. 1 Schematic of the Lake Lakhtinsky Razliv drainage basin. Lakes: (1) Verkhnee Susdalskoe, (2) Srednee Susdalskoe, (3) Nizhnee Susdalskoe, (4) Reservoir on River Kamenka, (5) Lakhtinsky Razliv. Rivers: (6) Starozhilovka, (7) Kamenka, (8) Tchernaya, (9) Yuntolovka, (10) Khaizovy, (11) Gluharka. Swamps: 12) Lakhtinskoye swamp. Sources of pollution: (13) urbanized areas, (14) urban rubbish dump, (15) cemetery, (16) sewage sludge disposal from the city's purification plant, (17) fields.

The choice of the drainage system of Lake Lakhtinsky Razliv as a main case study unit has been determined by the following factors (Kondratyev *et al.*, 1997):

- they offer characteristic types of both natural and urban landscapes as well as point and non-point sources of pollution;
- the main mechanisms of migration and transformation of substances can be investigated using this water system and to develop and check the methods of numerical evaluation.

The study drainage basin (area 163 km^2) is shown in Fig. 1. The main water courses are the rivers Starozhilovka, Kamenka and Tchernaya with the Lakes Suzdalskie, Verkhnee, Srednee and Nizhnee being the main natural lakes within the drainage basin.

METHODS

The dynamic flows in transporting elements have been estimated several times during the period of research (1996–1998) depending on temporal storm variation. Estimations of the state of the cumulative elements have been sampled on one occasion with later chemical analysis. Geochemical survey of snow cover has also been made at 10 locations, soils at 20 points, and bottom sediments (in lakes Suzdalskie and Lakhtinsky Razliv) at 16 sites. Evaluation of water quality has been made by comparison of the observed concentration of pollutants with national sanitary-limited permissible concentrations (*LPC*) as well as using an index of water pollution (*IWP*):

$$IWP = \sum_{1}^{n} C_i / LPC_i / 6$$

where C_i is the mean annual concentration of a chemical substance; $n = 6$ refers to a limited number of substances used for calculations but always including dissolved oxygen and BOD5.

For the evaluation of the state of cumulative elements (within snow cover, soil and bottom sediments) the coefficient $K_c = S_i/S_f$ has been used, where S_i = concentration of a substance in sample and S_f = a mean background concentration of a substance. The values of S_f have been determined as the concentration of the substances in soils or snow cover under natural conditions (at a distance of more than 50 km from the city). The differences have been considered reliable if $K_c > 2$. The coefficient of pollution Z_c has been calculated according to the equation:

$$Z_c = \sum_{1}^{n} K_{ci} - (n-1)$$

where n is a number of substances.

ATMOSPHERIC INPUT

The data concerning the pollution of snow cover have been used for the evaluation of the background atmospheric load on water bodies and land surface with snow sampling conducted during the period of maximum thickness of snow cover. The human impact on the atmospheric load has been determined using as an indicator the exceedance of snow cover pollution over background concentrations. The results would suggest that the maximum amount of heavy metals are falling onto the water surface of Lakes Suzdalskie. The coefficients K_c vary between 1.0–4.8 for Pb, 1.4–5.8 for Cu, and 2.7–11.0 for Mn. The spatial homogeneity for nitrogen and phosphorus concentrations are rather lower (K_c = 1.05–2.23 and K_c = 1.63–3.75 respectively).

GEOCHEMISTRY OF SOILS

The soil geochemical survey detected anomalous concentrations of Mn ($K_c > 2$ in 80% of samples and mean $K_c = 4.2$), Pb ($K_c > 2$ in 70% of samples and mean $K_c = 3.1$), V ($K_c > 2$ in 70% of samples and mean $K_c = 2.8$), Co ($K_c > 2$ in 80% of samples and mean $K_c = 2.3$) and Cr ($K_c > 2$ in 55% of samples and mean $K_c = 2.5$). The kernel of this geochemical anomaly is located in the sediment fields of the city's purification plant and urban waste disposal sites, where Z_c is equal to 118. The soil pollution here is classified as "polluted and dangerous". The area with $K_c > 2$ according to mono-element mapping occupies more than 70–80% of the drainage basin. The value of Z_c for the whole drainage basin is equal to 18 and the level of pollution is characterized as being "contaminated".

HYDROCHEMICAL CHARACTERISTICS OF SURFACE WATER

The concentrations of nutrients in river and lake waters are determined by nutrient loads and the processes of pollutant migration occurring from the upper part of the drainage basin to the lower part. The intensive human impact on the watershed of the River Starozhilovka leads to high inputs of nitrogen and phosphorus. The nutrients are subjected to biochemical transformation and partly enter the bottom sediments. In the first place this effect is characteristic for dissolved phosphorus. The reservoir on the River Kamenka (which comprises a barrier to downstream pollutant migration) shows an analogous influence in terms of a decrease in nutrient concentrations. According to the mean concentrations of total phosphorus for the discussed period, Lake Verkhnee (0.027 mg l^{-1}) and Srednee (0.023 mg l^{-1}) are mesotrophic; Lake Nizhnee (0.060 mg l^{-1}), the reservoir on the River Kamenka (0.035 mg l^{-1}) and Lake Lakhtinsky Razliv (0.054 mg l^{-1}) are eutrophic.

The concentration of organic matter in the receiving water of the studied water bodies varies from COD = 15–25 mg O_2 l^{-1} to COD = 26–70 mg O_2 l^{-1}. The minimum COD (10.4–10.9 mg O_2 l^{-1}) was observed in July with a maxima in October (COD = 26.9–32.9 mg O_2 l^{-1}). However, the differences between mean concentrations of COD for all water bodies for the period of observations are not statistically significant. Nevertheless the organic matter contained in the lake waters is characterized as being strongly biochemically oxidizing.

Exceedances of the sanitary *LPC* for phenol have been observed for all the case study rivers and lakes. The maximum concentration of phenol has changed from 2*LPC* (Lake Lakhtinsky Razliv) to 10*LPC* (Lake Verkhnee Suzdalskoye and the reservoir on the River Kamenka). 10*LPC* has been registered for the River Tchernaya. The maximum exceedance of the sanitary *LPC* for oil in water has been determined for the River Starozhilovka (to 6*LPC*) and in the Rivers Tchernaya and Kamenka (to 1.5*LPC*). The maximum concentration of oil in other rivers and lakes has not exceeded the *LPC* value.

A peculiarity of the pollution structure of the researched drainage basin is the exceedance of *LPC* and for Fe and Mn which is connected with the important role of swamp waters in river input. The concentrations of other metals are at background levels excluding the River Tchernaya which is polluted by Fe (to 25*LPC*), Mn (to 60*LPC*), Al (to 10*LPC*), K (to 8*LPC*), Cr (to 2*LPC*), Cd (>*LPC*). This is the result not only of swamp feeding of water bodies but also due to pollution from the waste sediment fields referred to earlier. The calculated Water Pollution Indices (*IWP*) are shown in Table 1 as well as characteristics of water quality. According to the *IWP*, the researched water bodies can be classified as being "moderate contaminated" (Lake Verkhnee) and "contaminated" (Lakes Srednee, Nizhnee, reservoir on the River Kamenka). Lake Lakhtinsky Razliv can be refereed to as being in the "contaminated-polluted" class of water quality and is in a state of anthropogenic ecological regress with the total hydro-ecological situation being characterized as in crisis.

GEOCHEMISTRY OF BOTTOM SEDIMENTS

The bottom sediment of urban lakes, especially those of Verkhnee and Srednee, contain a considerable amount of organic matter. The maximum content of phosphorus

Table 1 Characteristics of water bodies in the drainage system of Lake Lakhtinsky Razliv.

Water body	Water surface area (km^2)	Mean / maximum depth (m)	Drainage basin area (km^2)	*IWP* (water quality state)	Z_c (state of sediment pollution)
Verkhnee	0.22	5.5 / 12.0	0.48	1.8 (moderately contaminated)	156 (extremely polluted, dangerous)
Srednee	0.13	4.0 / 6.5	0.86	2.5 (contaminated)	153 (extremely polluted, dangerous)
Nizhnee	0.74	2.2 / 5.2	35.5	2.2 (contaminated)	69 (very polluted, dangerous)
Reservoir on the River Kamenka	0.33	1.8 / 4.0	50.0	3.1 (contaminated)	–
Lakhtinsky Razliv	1.8	4.3 / 8.5	163.0	4.0 (contaminated - polluted)	31 (polluted, dangerous)

(to 3.4 mg P kg^{-1}) is observed in the bottom sediment of Lakes Verkhnee and Nizhnee. The concentration of P in pore solutions of the bottom sediment are not sufficient due to a high content of Fe and Mn. There are periodical appearances of anaerobic conditions which lead to the dissolution of phosphorus from the bottom sediments into the overlying lake water. The pore solutions of bottom sediment contains a lot of ammonium with concentrations in Lakes Verkhnee and Srednee reaching 19.6 mg N l^{-1}. The concentration of phosphorus and nitrogen in the pore solutions of the upper (2 cm) layer of the bottom sediment is higher than in bottom layers of the lake water which guarantees the continued upward diffusion of P and N into the lake waters.

The degree of bottom sediment pollution is determined as the exceedance concentrations over background. Table 1 shows the calculated values of Z_c and appropriate estimates of pollution degree. Heavy metal anomalies recorded in the bottom lake sediment have a multi-element composition. For the upper (Lakes Suzdalskie) and lower (Lakhtinsky Razliv) parts of the water system, they are represented by different associations of elements. Mn and Co are common for both parts with highest values of K_c being characteristic for all parts. The bottom sediment of Lakes Suzdalskie contain Pb and Zn typical of urban territories. The high concentrations of Pb are undoubtedly connected with the influence of two highways between which Lakes Verkhnee and Srednee are located. The concentration of Pb in the bottom sediment profile of Lake Nizhnee is 1.5 times lower than for the two upper lakes. The main reason for this is that the lake is under the impact of only one highway. Table 1 shows that the values of Z_c for Lakes Suzdalskie bottom sediment are essentially higher than for Lake Lakhtinsky Razliv. This phenomenon is connected with the high external load and the cumulative role of the upper parts of the drainage system and the small overflow for this lake.

The spatial survey of bottom sediments in Lake Lakhtinsky Razliv has exposed the complex mechanism of their formation which is connected with the peculiarities of the lake's hydrodynamic regime. The highest concentrations of pollutants in the bottom sediment are characteristic of the northern part of the lake where the frontal interaction of water masses coming in from the Neva Bay and by inflowing rivers takes place.

CONCLUSIONS

The implemented research makes it possible to evaluate the current state of St. Petersburg water bodies and particularly to identify the water system of Lake Lakhtinsky Razliv as being in crisis and in a stage of anthropogenically induced ecological regress. However, the water bodies have not lost their total potential for self-purification. It has been found that Lakes Suzdalskie and the reservoir on the River Kamenka interpose geochemical barriers on the migration pathways of nutrients and pollutants from the upper part of the drainage basin to Lake Lakhtinsky Razliv and then down to the Neva Bay. The water bodies intercept, transform and accumulate in the bottom sediment, the majority of these incoming pollutants from the upper part of the drainage system and which are generated a result of intensive technogenic and urban pressures.

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