Hydrogeological Modeling of the Spread of Pollution from the Historical Landfill Towards the Lakhta Spill, St. Petersburg, Russia

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Abstract. Nowadays, the areas subjected to severe anthropogenic disturbance, such as waste landfills, do not meet both the environmental and human health standards and are associated with concepts of "environmental degradation", "pollution" and "environmental risk". In turn, the geochemical influence is associated with almost all types of technogenesis, has a widespread occurrence, occurs during the entire period of use of the territory and affects all components of the natural complex. Taking into account both geological and hydrogeological features of the study areas, predictions of contaminants migration from the historical waste landfills of St. Petersburg to the catchment area of the Gulf of Finland have been compiled. The results demonstrated the usefulness of a step-by-step method, involving increasingly detailed geochemical "portraits" of anthropogenically modified objects, as well as the creation of training geochemical set to predict the changes of functional zones contour.

1. Introduction
One of the global problems in the management of old urban and industrial wastes disposal/storage sites is the absence of environmental concerns at the time of their construction/settlement.

As a result, such sites became unmanaged accumulators of elements derived from anthropogenic activities. Indeed, according to the thermodynamic law of energy conservation and transformation, the energy of chemical bonds, in complex organic and mineral compounds is constantly changing under the influence of external factors and it is extremely unstable. Also, if we take into account the thermodynamic features of waste disposal facilities, we can conclude that these systems can be stabilized with low entropy, i.e., constant and efficient energy dissipation as a result of substance oxidation of the waste mass. Thus, waste disposal sites, if considered as isolated thermodynamic systems with a huge stock of potential energy, cannot always be in a stable state [1,2,3]. Therefore, taking into account the qualitative structure and ecological status of the territories where old landfills have been settled, it is expectable to have negative impact of these structures in the environment. Also, the creation of new geochemical barriers, as one of the stages of reclamation of urban and industrial waste landfills, often carries additional anthropogenic pressure to the impacted systems [3,4]. This is mainly due to insufficient studies on the conditions of the lithosphere upper horizons and on migration of pollutants, thus leading to new environmental problems.
2. Materials and methods
Representative sites of three different functional geoecological zones in St. Petersburg were selected, on the basis of close geomorphological, geological and hydrogeological conditions, but with distinct levels of anthropogenic impact, namely:

1. Industrial functional zone (Historical Municipal Solid Waste Landfill (MSWL) "Novoselki" (food and packaging waste, packaging, waste paper, household and office garbage) and Sewage Sludge Landfill "Severn\'y" (SSL);
2. Residential functional zone (adjacent to the landfills area (MSWL+SSL), hereafter designated as "Residential");
3. Recreational functional zone (Novoorlovskaya Special Economic Zone (SEZ), a part of Novoorlovsky Forest Park).

To assess the contamination of soils analysis for the presence of two organic compounds (petroleum and polycyclic aromatic hydrocarbon (PAH) - benzo (a) pyrene) and 10 heavy metals (mercury, lead, arsenic, cadmium, zinc, nickel, cobalt, chromium, copper, manganese) were performed. The assessment of the danger of soil contamination for public health, due to metals were also carried out using the total pollution (Zc) indicator.

3. Results and discussion

3.1. Comprehensive environmental assessment
The actual assessment of the levels of chemical pollution of the territories of domestic and industrial waste landfills was based on a comparison of the existing pollution with the regional and local background geochemical levels for the objects, as well as maximum permissible concentrations (MPC). On the territory of MSWL, the concentrations of pollutants in all the studied horizons remain at a high level, exceeding the MPC for individual elements up to 50 times. According to the degree of chemical pollution, the soils of the territory of the Novoselki landfill, in all horizons, are considered as "extremely dangerous": the content of organic compounds of the first hazard class exceeds 5 MPC, the total pollution indicator taking into account toxicity (Zct) of pollutants takes values over 128.

On the territory of the storage site of SSL the pollution halo is located in the horizons at 1m deep, in the "old" north-western part of the silt sites. Results show that the territories adjacent to the landfills, namely the bottom sediments in the Chernaya River, as well as the surface water, are polluted with heavy metals. The source of pollution is the landfill "Novoselki". When the landfill area was expanded in the mid-2000s, the western part was subjected to environmental engineering works, which were carried out in part: there are no clay bank and a second ring of diversion ditches in the north-western sector. Thus, the landfill leachate and surface runoff are in direct contact with the swamp waters of the surrounding area.

In addition, two ditches exit directly from the internal drainage system of the landfill, in the direction of the Chernaya River. The original drainage system of the landfill is damaged and pollution of natural surface watercourses far beyond the limits of the landfill becomes inevitable.

Analysis of the results of the initial mathematical processing of data and in-depth descriptive statistics, the distribution of heavy metals and organic pollutants in soils and soils of different functional areas studied, as well as artificially maximizing the distinctive properties, by comparing the geochemical series of pollutants with respect to the regional and local geochemical background of recreational zones, allows us to distinguish indicator elements for each of the anthropogenically modified geological bodies. At the studied sites of all functional zones, changes in the location of elements in geochemical series can be considered insignificant and associated with the introduction of pollutants from the air environment. For the MSWL "Novoselki" As, Ni and Cr are the marker elements; for the silt sites of the SSL "Severn\'y" - As, Ni and Cr.

The use of factor and cluster analysis in geocological studies can highlight hidden patterns and reduces the need for geochemical information, by describing the process by factors whose number is significantly lower than the initial ones. The resulting paragenetic associations contain the distinctive
features of the objects under study and the structure of the relationships between the variables that are characteristic of each of the functional zones (table 1).

| Study Areas       | Significant variables | Non-significant variables |
|-------------------|------------------------|----------------------------|
| MSWL "Novoselki"  | Ni                     | Hg, Pb, As, Cd, Zn, Co, Cr, Cu, Mn, Benz, Petrol |
| SSL "Severn"      | As, Pb, Co             | Cd, Zn, Ni, Cu, Mn, Benz, Petrol |
| Adjacent areas    | Pb, Cr, Hg, Ni, petrol, Zn | Cu, Benz |
| SEZ "Novoorlovskaya" | Cu, Zn, Pb, Mn       | Hg, Cd, Ni, Co, Cr         |

3.2. Hydrogeological modeling

The analysis of the features of the upper horizons of the lithosphere and the construction of a geological section for the study area, in Novoselki solid waste landfill included a large number of published literature [5], including reports and engineering-geological and engineering-hydrological surveys, in part of which the authors were directly involved [6,7].

According to the results of the compilation of geological and hydrogeological data, layered geological maps and detailed sections of the entire thickness of the Quaternary sediments were compiled for one anthropogenically modified geoecological object: the Novoselki landfill. This step is critical for the construction of models for estimate both matter migration and the actual mass transfer of pollutants. The underlying parent rocks are represented by marine and lake sediments (layered and band clays and loams) and organogenic rocks (peat). After a detailed description of the existing geochemical situation in industrial functional zones, all geochemical information was superimposed on the models of the structure of the upper horizons of the lithosphere of the study areas.

The modeling area for both MSWL and SSL was 50 km²: from the border of SSL to the Lakhta spill, including Yuntolovskoye bog and the entire area of the Yuntolovskiy reserve. The simulation grid included 1250 unit cells (200 * 200 meters). Migration of pollutants was traced through 3 horizons: surface sediments (the area of localization of anthropogenically modified geoecological objects); water-glacial (lacustrine-glacial and fluvioglacial) over-morain deposits of the Ostashkov stage; The Moscow-Ostashkov intermoral water-bearing locally-waterproof horizon ("Polyustrovsky" horizon) (Figure 1). The model took into account possible "windows" in the Ostashkovsky moraine to the east and southeast of the boundary of the landfill.

The terrain was modeled using Google Earth 7.1.8.3036, the depth of each of the horizons of the model was taken relative to the stock and literature materials [5,7]. For each unit cell of the model, certain values of filtration coefficients and effective porosity were specified depending on geological conditions. The average distribution coefficients (Kd) of heavy metals and organic pollutants for underlying mother rocks that are closest to the studied types were taken based on numerous studies by foreign scientists and experimental data [6]. Figure 1 shows the details of the geological conditions of the surface horizon of the simulation area both "Novoselki" and "Severn" landfills.
Despite the fact that the underlying landfills of Novoselki and Severny are loams and band clays, after 25 years, significant migration of pollutants to the Upper intermoral water-bearing horizon (Moscow-Ostashkovo inter-sea aquifer or Polustrovskiy horizon) in quantities of more than 5 times the background were observed (Figure 2). The same situation is observed for the two other indicator elements As and Cr.
Figure 2. Nickel migration in the surface horizon of the localization of anthropogenically modified geoecological objects.

For the next 5-10 years, it is possible to anticipate an increase of the pollution halo by 100–200 meters in a southwest direction. With a time span of more than 25 years, the increase is of 400-1000 meters (Figure 2). In the northern direction, the spread of anthropogenic pressure does not exceed 200 m. This is explained by the hydrogeological features of the model and the presence of wetlands in the north of the mud sites, which contribute to the accumulation of some heavy metals and organic pollutants.

On the model maps of nickel migration in the surface horizon (Figure 2), it is clearly seen that the Chernaya River adjoining the MSW landfill from the south is experiencing the greatest negative impact. Moreover, in contrast to the eastern part, in the western part of the MSW landfill there is only an internal ring of the drainage system [6], which is connected with the Chernaya River by a stream. The increase in pollution halo in the future will increase the amount of heavy metals and organic pollutants introduced into the surface watercourse, which will have a negative impact on the Lakhta spill ecosystem.

Groundwater in the city should be considered as a "pool" of polluted waters, from which downward filtration is possible, provided that their level is located above the piezometric surface of the underlying aquifers. Pollution can even reach the Vendian aquifer complex, if reservoirs have weaknesses, as well as in the case of their decreased thickness, which is observed in the buried valleys [5,8].

As for the underlying horizons, despite the underlying polygons of loam and band clays in the above-bedded sediments of the Ostashkov stage, after 25 years, significant migration of pollutants, in concentrations, at least five times higher than the regional background values, is possible. Even without
hydrogeological windows in the Ostashkov Moraine, in a long term basis, migration of heavy metals into the underlying Polustrovskiy aquifer is possible. This migration largely relates to heavy metals and will depend on their content in geocological objects (in this case, landfill bodies). Even after 25–50 years, a stable and significant addition of chromium to the aquifer is noted. Of course, chromium concentrations are significantly lower than the MPC, but more than 5 times higher than background values [9,10].

4. Conclusions
The solid waste landfills are an anthropogenically modified geocological system, including a geocological object of natural and man-made origin, the underlying rocks and adjacent territories. From a modelling point of view, all geocological objects and the upper horizons of the lithosphere, have a zonal geochemical structure and are similar. For their evaluation, we apply a basic approach of functional zoning, whose scale characteristics can be increased to the entire area of hypergenesis. Using the case study of heterogeneous anthropogenically modified objects such as landfills, it is possible to isolate functional zones (integral geochemical excretion within the territories of megalopolises), create matrices of substance migration flow and predict their movement, as well as to assess the sustainability of ecosystems.

According to the results of creating models of functional zones for the studied areas, it is possible to create adjustments to sanitary protection zones of land plots, depending on the existing categories of land and their modes of use. Subsequently, during the urban development of the megacity area, the sanitary zone may be adjusted for local functional zonality and the characteristics of the underlying parent rocks. That is, a certain zero background is created for the sanitary protection zone, different to each part of the functional model, contributing to an adjustment of the final sanitary protection zone for the designed structures and facilities.

5. References
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