Assessment of the spread of pollution in the riverbed of the Neva River as a result of an emergency at a toxic waste landfill

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Abstract. The catchment area of the Neva River, which includes the largest European lakes Ladoga, Onega, Ilmen and Saimaa, located in Finland, has an area of 183,300 km². The quality of water in the Neva River is determined by the characteristics of the water masses of Lake Ladoga, as well as by point and non-point sources of pollution on the tributaries of the Neva. One of the potential sources of pollution is the Krasny Bor landfill for storing highly toxic waste of hazard classes I – V. In the event of an emergency at the landfill, toxic wastewater can enter the Izhora River, and then into the Neva River, 7 km above the water intakes of St. Petersburg. Using the methods of mathematical modeling, the calculation of the spread of toxic substances in the hydrographic network of the catchment area, and then in the channel of the Neva River was carried out under various scenarios of the development of an emergency at the landfill. A full-scale experiment was carried out to confirm the adequacy of the model of impurity spreading in the channel of the Neva. An assessment of the features of the transport of suspended particles and dissolved impurities in the direction of the water intakes of St. Petersburg is given.

1. Introduction
Reception basin of Neva River (Novosaratovka section line), including the biggest European lakes Ladoga, Onega, Ilmen and Saimaa, located in the territory of Finland, has the area of 183,300 km² (without water area). Channel density amounts to 0.45 km/km² in average. The quality of Neva waters is characterized by water mass of Ladoga Lake, as well as point and nonpoint sources of pollution in Neva tributaries. One of potential pollution sources is the Krasny Bor toxic waste landfill for high-toxic waste of hazard classes I to IV, located 30 km far from Saint-Petersburg and 15 km far from the Izhora estuary, wheerethrough landfill emergency discharge is possible. This is the only one enterprise for hazardous waste burial in the territory of Northwestern Federal District. The landfill contains approx. 2 million tons of toxic waste, which were delivered from the whole territory of Russia and even Baltic states starting from 1969 [1, 2].

The purpose of this study is simulative evaluation of spreading of possible emergency toxic discharge from Krasny Bor landfill towards Saint-Petersburg water intakes located in Neva River.

2. Materials and Methods
Krasny Bor landfill was created in 1967 as temporary facility (temporary waste deposit). Service life of experimental landfill, as defined by project assignment, amounted to three years. However, due to
the absence of alternative enterprise, the landfill was used actively until 2015 [1]. Currently, 5 open reservoirs survived in Krasny Bor landfill: Nos. 59, 64, 66, 67 and 68. Their location is represented in figure 1, main parameters are included into the table1. Other reservoirs are closed.

![Figure 1. Location of open reservoirs of the the Krasny Bor toxic waste landfill.](image)

**Table 1. Parameters of open reservoirs of the the Krasny Bor toxic waste landfill**

| No of open reservoir | Year of opening | Reservoir volume (m³) | Reservoir depth (m) |
|----------------------|-----------------|-----------------------|---------------------|
| 59                   | 1986            | 8112                  | 8.5                 |
| 64                   | 1988            | 445 360               | 24                  |
| 66                   | 1990            | 10 725                | 6.5                 |
| 67                   | 1991            | 32 400                | 9                   |
| 68                   | 1992            | 106 360               | 10                  |

As is mentioned in [1], actual volumes of open reservoirs significantly exceed design ones, as open reservoirs were dammed to increase their capacity. Damming height around active reservoirs Nos. 64, 68, 66, 67, and 59 is up to 5 m. The same source [1] indicates that open reservoirs were dammed with violation of standards: sand band, laying directly under Cambrial clays and watertight moranic deposits widely distributed over the landfill territory, is not removed. These sands serve as collectors for polluted filtrate crossflow both between closed reservoirs, and beyond them [2].

To intercept surface and ground water runoff from the landfill, 2.5-3.5m deep ring channel is installed along external edge of the landfill. Channel’s drain is equipped with gateway system and locking device. Ring channel is connected to drain main. Further, the effluent from the landfill flows up to Neva River along Bolshoy Izhorets stream and Bolshaya Izhorka and Izhora Rivers. Their properties are represented in table 2.

When emergency occurs in the landfill, toxic effluents can enter to Izhora River and then to Neva 7 km upstream the Saint-Petersburg water intake (figure 2).
Table 2. Characteristics of the route sections of the possible spreading of the emergency discharge

| Watercourse          | Length (km) | Average width (m) | Average slope (‰) | Discharge (m³/sec) |
|----------------------|-------------|-------------------|-------------------|-------------------|
| Main channel         | 2.63        | 0.50              | 1.7               | 0.063 0.049 0.028 |
| B. Izhorets creek    | 8.24        | 1–3               | 1.3               | 0.088 0.069 0.039 |
| B. Izhorka Riv.      | 3.13        | 2–5               | 0.3               | 0.297 0.231 0.131 |
| Izhora River         | 0.64        | 20–50             | 0.2               | 10.1 8.64 5.24   |

Figure 2. Layout of the Krasny Bor landfill: 1 – water intakes in St. Petersburg, 2 – the route of the spread of a possible emergency discharge to the Neva River

Polluted substance distribution to main channel via diversion duct and small water ducts was calculated using the Saint-Venant system of equations in one dimension sounding [3-7] supplemented with dissolved impurities spreading model based on turbulent diffusion equations [8].

Polluted Izhora waters distribution in Neva River was calculated based on water and sediment motion model in two dimensions sounding [9,10] based on mathematical representation of forces acting in the system ‘water flow – bottom sediments – deposits’, also supplemented with dissolved impurities spreading equations [8].

Calculations were made for occasional concentration of conservative pollutant in discharge. This enables easy recalculation of acquired simulation results to needed discharge concentration. Pollutant non-conservativity can be accounted by introduction of exponential concentration relationship into turbulent diffusion model [8] for reduction evaluation in the form \(\exp(Kn \cdot x/v)\), where \(x\) is longitudinal
ordinate (m) and v is velocity (m/s). Meantime, non-conservativity factor, \( Kn \) (1/sec), in connected to disintegration (conversion) rate value, \( K \) (1/day), with the following equation \( Kn = -1.16 \times 10^{-5} K \).

Disintegration rate \( K \) and non-conservativity factor \( Kn \) values for some toxicants are represented in table 3.

| Toxicant               | Disintegration (conversion) rate \( K \) (1/day) for \( T < 10^\circ \text{C} \) | Non-conservativity factor \( Kn \) (1/sec) |
|------------------------|-------------------------------------------------|----------------------------------------|
| Petroleum hydrocarbons | 0.02                                            | -2.32E-07                              |
| Synthetic surfactants  | 0.3                                             | -0.00000348                            |
| Ammonium               | 0.9                                             | -0.0001044                             |
| BOD                    | 0.2                                             | -2.32E-06                              |
| Phenols                | 0.2                                             | -2.32E-06                              |
| COD                    | 0.1                                             | -1.16E-06                              |

3. Results and Discussion

Calculations performed for three of the most probable emergency development scenarios in the landfill, which were defined by specialists of Russian State Hydrometeorology Institute based on multi-year field survey in the landfill and adjacent territories [11, 12]:

- **Scenario 1.** Damming overflow of toxic waste storage reservoirs due to intensive precipitation, separately or in conjunction with increased snow storage on reservoir surfaces. Level increase above damming is possible in open reservoirs (Nos. 59, 66, 67) at intermittent daily maximal precipitation. Reservoirs 64 and 68 are covered by floating pontoons, wherefrom atmospheric precipitations are pumped out and there is no threat of overflow. Risk factor exposure time is up to 96 hours. Precalculated precipitation maximum within 96 hours: March: 0.104 m; April: 0.116 m; May 0.224 m; June: 0.176 m; July: 0.276 m; August: 0.312 m; September 0.136 m. Snow reserve at the beginning of March is 0.66 m with water reserve of 0.08 m. Volume of toxicants that can ingress to bypass and internal drain channels from the surface layer of reservoirs content at theoretically possible level increase by 0.10 m shall amount: 142 m³ for reservoir No 59, 260 m³ for reservoir No. 66, and 392 m³ for reservoir No. 67. Total emergency discharge will be 794 m³ per 96 hours.

- **Scenario 2.** Damming destruction of toxic waste storage reservoirs due to intensive precipitation in spring period, separately or in conjunction with increased snow storage on reservoir surfaces. This scenario assumes that damming destruction can be in overflow conditions only. Damming destruction depth represents calculation parameter. Risk factor exposure time is up to 100 hours. The rest reference conditions comply with previous scenario. Total emergency discharge is 7940 m³ per 100 hours.

- **Scenario 3.** Damming destruction of toxic waste storage reservoirs due to emergency (terrorist attack, explosion, tsunami, etc.) down to full damming destruction up to ground elevation for the reservoirs under consideration. The rest reference conditions comply with previous scenario. Total emergency discharge is 176985 m³ per 100 hours.

Figure 3 represents calculation results for dilution degree of the pollutants entering to hydrographic section of the reception basin according to the above-mentioned scenarios of emergency discharge from the landfill for main channel, Bolshoy Izhorets stream, Bolshaya Izhorka and Izhora Rivers with different discharge rates of different occurrence. Occasional substance concentration is accepted as initial effluence concentration. Besides calculations of soluble impurities spreading, carryover of
suspended particulates, coming with Izhora effluent and being potential carrier of toxicants occluded thereon was calculated for Neva River. Typical feature of the process of suspended particulates and soluble impurities carryover by basic Neva current is that inflow waters are flowing down to a shore and distributed along this at minimal mixing with water masses of main flow. This feature related to the along-shore pollution spreading is confirmed by experiments in previous stages of the study [13, 14]. Figure 3 represents evaluation of possible dilution of an emergency discharge entered from Izhora, in coastal area of Neva River, 12 m wide and 7 km long, up to the closest municipal water intake of the Northern Water Station (NWS).

![Figure 3](image-url)

**Figure 3.** Results of calculations of pollutants dilution using scenarios 1, 2 and 3 from landfill until the nearest water intake (water availability are 50, 75 and 97%)

As was expected, the most unfavorable situation with dilution occurs in realization of the third scenario of possible emergency discharge from the landfill, which occurs because of complete damming destruction of toxic waste storage reservoirs Nos. 59, 64, 66, 67 and 68. In this case, increasing water content positively effects onto dilution degree.

The calculations also showed that all suspended particulates coming into the estuary with Izhora effluent deposit in coastal area not more than 0.5 km far from tributary influx location.

Figure 4 represent dependence of emergency discharge spreading time (unit volume but not flow routing wave) in concerned water system with different water content. In the case of average water content (occurrence 50%), discharge need 14.3 hours to reach Neva and 17.8 hours to reach the closest water intake of Northern Water Station. Decreasing water content leads to significant increase in lag time, as for effluent occurrences of 75 and 97% the value of effluent lag time increases to 22.1 and 36.9 hours, respectively.
4. Conclusion
Calculation of toxicants spreading in hydrographic network of watershed and in Neva River was made using mathematical simulation methods for three scenarios of emergency development in the landfill. Typical feature of the process of suspended particulates and soluble impurities carryover by basic Neva current is that inflow waters are flowing down to a shore and distributed along this at minimal mixing with water masses of main flow. It was shown that the most unfavorable situation with dilution occurs in realization of the third scenario of possible emergency discharge from the landfill, which occurs because of complete damming destruction of toxic waste storage reservoirs. Decreasing water content negatively effects to dilution degree. Calculation results, represented in figure 3, can be easily recalculated to any real discharge concentration values, as they are represented in unit fractions. Suspended particles, entering to Neva River with the Izhora effluent, do not pose direct threat for water intakes, as they don’t reach them.

At average water content, emergency discharge from the landfill reaches the closest municipal water intake approx. in 18 hours. Decreasing water content leads to significant increase in lag time, therefore, definite time reserve is in place to take specific measures and intercept discharged effluents in hydrographic network or protect water intake. Besides this, water intakes shall be located beyond the areas of along-shore spreading of tributary waters to avoid pollutants ingress to water intakes.

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