Assessment of health risks associated with soil contamination by heavy metal in an impact area of Novocherkassk power plant

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Abstract. Soil contamination with heavy metals (HM) due to emissions of fired power plants poses risks to ecological safety and human wellbeing. Total concentration of Cr, Mn, Ni, Cu, Zn, Cd, and Pb in twelve surface soils (0–20 cm) around the Novocherkassk Power Plant (NPP) was determined using X-ray fluorescence spectrometry. According to the level of non-carcinogenic risk for all age groups, metals form the following series in descending order: Pb > Ni > Mn > Cu > Cd > Zn > Cr. The total risk of general toxic effects of all studied elements for both age groups is assessed as low. The carcinogenic risk due to the combined exposure to Ni, Cd and Pb slightly exceeds the permissible level of $1 \times 10^{-6}$ in the soils in the immediate vicinity of the plant, but in general, it corresponds to the acceptable level in the study area.

1 Introduction

Fossil fuel electricity production is one of significant sources of environmental pollution, especially when coal is used. Combustion of coal leads to the emissions of acid and greenhouse gases, bottom ash, and fly ash, containing HM [1–3], which accumulate in surrounding soils. Coal-fired power plants are often located in areas with high population density [4], affecting the land use and endangering the human health [5].

Novocherkassk Power Plant (NPP) located near one of the largest cities in the Rostov Region with a population of 167000 people. Novocherkassk is characterised by the increased level of atmospheric pollution, which is estimated to be 6.47 Kt of particulate per year [6]. Previous studies of NPP impact area indicate an increase in HM concentrations in natural systems [3, 7–9], but health risk assessment has never been carried out.

A number of HMs typical of emissions from coal-fired power plants, such as Cr, Mn, Ni, Cu, Zn, Cd, and Pb, are considered the most hazardous HM in accordance with Russian

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environmental and hygienic standards [10]. This study was attempted to evaluate possible carcinogenic and noncarcinogenic risks related to HMs in soils around NPP.

2 Methods

2.1 Soil sampling and analytical methods

Field studies were performed at 12 monitoring sites laid along the radii emanating from the NPP chimneys in various directions and distances. Soil samples were collected in June 2019 using an envelope method from the surface soil horizon (0–20 cm deep). The soil samples were air-dried, mixed, ground and passed through a 1-mm sieve [11]. The total concentrations of Cr, Mn, Ni, Cu, Zn, Cd, and Pb were determined by X-ray fluorescence analysis using a Spectroscan MAX-GV spectrometer (Spectron, Russia) [12]. The accuracy of HM determination was verified using duplicates, reagent blanks, and state standard reference samples, and complies with standards of certified methods [12]. Descriptive statistics were calculated with STATISTICA 12 StatSoft (USA) package.

2.2 Health risk assessment

Human health risk assessment is a process made up of four basic steps: data collection and analysis, toxicity assessment, exposure assessment, and risk characterisation [13]. Toxicity assessment is a quantitative estimation of the likelihood of adverse effects occurring in humans at different exposure levels to contaminants [13]. The reference dose ($RfD$, a noncarcinogenic threshold) and the cancer slope factor ($SF$, a carcinogen potency factor) are two important toxicity indices used. The values of $RfD$ and $SF$ for oral intake were established by the US EPA and other regulators based on toxicological studies (Table 1).

| Metal | $RfD_{ing}$ | $RfD_{derm}$ | $RfD_{inh}$ | $SF_{ing}$ | $SF_{derm}$ | $SF_{inh}$ | Reference |
|-------|------------|-------------|-------------|------------|------------|------------|-----------|
| Cr(III) | 1.5 | 0.038 | 0.0014 | – | – | – | [14–15] |
| Mn | 0.14 | 0.0084 | 0.04 | – | – | – | [15] |
| Ni | 0.011 | 0.00044 | 0.000026 | – | – | – | 0.84 | [14–16] |
| Cu | 0.01 | 0.002 | – | – | – | – | [14] |
| Zn | 0.3 | 0.06 | – | – | – | – | [15] |
| Cd | 0.001 | 0.00005 | 0.000029 | – | – | – | 6.3 | [14–15] |
| Pb | 0.0036 | 0.00072 | – | 0.0085 | 0.043 | 0.042 | [16–17] |

The purpose of exposure assessment is to measure or estimate the intensity, frequency, and duration of human exposures to HMs through ingestion ($RfD_{ing}$), inhalation ($RfD_{inh}$), and dermal ($RfD_{derm}$) contact by adults and children six years old and younger [13]. In order to assess the general toxic effects of soil metals, average daily doses ($ADD$) were calculated for three exposure pathways for both age groups according to the following formulas:

$$ADD_{ing} = \frac{(C) \times IR \times EF \times ED \times CF}{(BW \times AT)} \quad (1)$$
The results of determining the total HM content in surface soils of the NPP impact area are presented in Table 2. The content of HMs varies slightly, the differences between the mean and median are insignificant. The maximum HM content is observed in soils at a distance of 2 km to the west of the NPP (sites 4 and 5). At the same time, in the soils of the monitoring sites located at the same distance from the pollution source, but on the windward side, 1.5 times lower HM contents are observed. With the distance from the NPP, the HM content, in general, decreases.
The doses of metals entering the human body during interaction with the soil were calculated (Table 3). An analysis of the ADD and LADD values shows that both for different age groups and throughout life, the highest doses of HM potentially enter the body through ingestion, and the smallest dose through inhalation. The values of the ADD, both for individual HMs and in general, are higher for children than for adults. It should be noted that the ADD of metals are proportional to their content in soils.

Table 2. Statistical summary of HM concentrations (mg/kg, except for CV in %) in soils of the NPP impact area.

| Metal | n  | Mean | Median | Min | Max  | SD  | CV  | SE  |
|-------|----|------|--------|-----|------|-----|-----|-----|
| Cr    | 12 | 115.4| 115.2  | 84.0| 154.0| 20.7| 18.0| 6.0 |
| Mn    | 12 | 827.0| 825.9  | 598.0|1044.1|165.3|20.0|47.7|
| Ni    | 12 | 58.4 | 56.9   | 31.0| 91.0 | 18.7| 32.0| 5.4 |
| Cu    | 12 | 53.0 | 54.3   | 30.0| 80.0 | 14.0| 26.5| 4.1 |
| Zn    | 12 | 108.7| 112.0  | 70.1| 155.0| 24.1| 22.2| 7.0 |
| Cd    | 12 | 0.80 | 0.60   | 0.35| 1.85 | 0.49| 61.3| 0.14|
| Pb    | 12 | 41.9 | 38.0   | 18.0| 73.0 | 16.8| 40.1| 4.8 |

Table 3. Average health risk exposure (mg/kg/day) to noncarcinogenic hazards (ADD) for adults and children and carcinogenic hazards over a lifetime (LADD) attributed to the HMs from soils in the NPP impact area.

| Receptor | Dose | Cr     | Mn     | Ni     | Cu     | Zn     | Cd     | Pb     | Total |
|----------|------|--------|--------|--------|--------|--------|--------|--------|-------|
| Children |      |        |        |        |        |        |        |        |       |
| ADDing   | 1.5E-03 | 1.1E-02 | 7.5E-04 | 6.8E-04 | 1.4E-03 | 1.0E-05 | 5.4E-04 | 1.5E-02 |
| ADDderm  | 7.0E-05 | 2.5E-04 | 3.5E-05 | 1.6E-05 | 3.3E-05 | 2.4E-08 | 4.3E-05 | 4.5E-04 |
| ADDinh   | 4.5E-08 | 3.2E-07 | 2.3E-08 | 2.1E-08 | 4.3E-08 | 3.1E-10 | 1.6E-08 | 4.7E-07 |
| ADDtotal | 1.5E-03 | 1.1E-02 | 7.8E-04 | 6.9E-04 | 1.4E-03 | 1.0E-05 | 5.8E-04 | 1.6E-02 |
| Adults   |      |        |        |        |        |        |        |        |       |
| ADDing   | 1.4E-04 | 9.9E-04 | 7.0E-05 | 6.4E-05 | 1.3E-04 | 9.6E-07 | 5.0E-05 | 1.4E-03 |
| ADDderm  | 1.2E-05 | 4.2E-05 | 5.9E-06 | 2.7E-06 | 5.5E-06 | 4.0E-09 | 7.2E-06 | 7.5E-05 |
| ADDinh   | 1.6E-08 | 1.2E-07 | 8.3E-09 | 7.5E-09 | 1.5E-08 | 1.1E-10 | 5.9E-09 | 1.7E-07 |
| ADDtotal | 1.5E-04 | 1.0E-03 | 7.6E-05 | 6.6E-05 | 1.4E-04 | 9.6E-07 | 5.7E-05 | 1.5E-03 |
| Lifetime  |      |        |        |        |        |        |        |        |       |
| LADDing  | 1.7E-04 | 1.2E-03 | 8.4E-05 | 7.6E-05 | 1.6E-04 | 1.1E-06 | 6.0E-05 | 1.7E-03 |
| LADDderm | 9.3E-06 | 3.3E-05 | 4.7E-06 | 2.1E-06 | 4.4E-06 | 3.2E-09 | 5.8E-06 | 6.0E-05 |
| LADDinh  | 8.5E-09 | 6.1E-08 | 4.3E-09 | 3.9E-09 | 8.1E-09 | 5.9E-11 | 3.1E-09 | 8.9E-08 |
| LADDtotal| 1.8E-04 | 1.2E-03 | 8.9E-05 | 7.8E-05 | 1.6E-04 | 1.2E-06 | 6.6E-05 | 1.8E-03 |

To assess the noncarcinogenic risks, the ADD values obtained were compared with the RfD values. According to HQ, metals in descending order: Pb>Ni>Mn>Cu>Cd>Zn>Cr. The greatest risk for both children and adults is via ingestion of HMs (HQing 0.38 and 0.04), less through skin contact (HQderm 0.18 and 0.03) and insignificant via inhalation (HQinh <0.01). The risk of general toxic effects, taking into account all pathways of intake for adults, is
estimated as insignificant (HQ and HI less than 0.1) when assessing exposure to both individual metals and in total (Fig. 2). For children, HQ of Mn, Ni and Pb is assessed as low (average 0.11, 0.15 and 0.21, respectively), at the same time, exposure to other HM does not pose a significant risk. In general, the HM level in all soils of the NPP impact area corresponds to a low risk of manifestation of general toxic effects. The maximum HI values for children (0.72–0.88) are observed in soils in the near leeward zone of the NPP (Fig. 1).

Among the metals studied, only Ni, Cd and Pb have carcinogenic effects. Carcinogenic effects are caused by Ni and Cd only when inhaled, CR values vary within $3.6 \times 10^{-9}$–$5.7 \times 10^{-9}$ and $3.7 \times 10^{-10}$–$8.6 \times 10^{-10}$, respectively. The risks of carcinogenic effects associated with the intake of Pb from soils are ranked as follows, depending on the route of intake: $CR_{ing} \ (5.1 \times 10^{-7}$–$8.9 \times 10^{-7}) > CR_{derm} \ (2.5 \times 10^{-7}$–$4.3 \times 10^{-7}) > CR_{inh} \ (1.3 \times 10^{-10}$–$2.3 \times 10^{-10})$. The $TCR$ exceeds the threshold value of $1 \times 10^{-6}$ in the soils of the near zone of NPP (sites 4 and 5), which indicates the need for further monitoring of soils in this zone, while more remote sites are characterized by a minimal level of risk.

**4 Conclusions**

The ranking of metals in the soils of the NPP impact zone showed that the highest noncarcinogenic risk in the study area is observed from the effects of Pb, Ni and Mn. The cumulative noncarcinogenic risk for adults is assessed as insignificant for adults and low for children. The values of the carcinogenic risk due to exposure to Ni, Cd and Pb correspond to the target values for residential areas, with the exception of soils adjacent to the NPP, in which the $TCR$ reaches a value of $1.3 \times 10^{-6}$.

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