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Ecological hazard, typology, morphometry and quantity of waste dumps of coal mines in Ukraine

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Abstract. As a result of coal mining, a large number of waste rock dumps have been created on the earth's surface around the world. As a result of deflation and water erosion of the dump surface, extensive contamination of the soil cover of agricultural land with heavy metals occurs, threatening the food security of many countries. The article proposes a method for determining the area of potentially contaminated land in coal-mining regions. The area of such land in Ukraine has been estimated. A scheme for the dispersion of pollutants from waste dumps is proposed, which makes it possible to identify four types of polluted areas. Using the Google Earth service, the exact modern number of dumps in the Donetsk coal basin (Donbass) as a whole (1600) and separately in its western, central and eastern parts was determined. The average height, the average and total area of the base and surface, and the forest cover of the dumps in the Central Donbass were determined. It was found that the area of potentially contaminated land as a result of surface deflation of dumps in Central Donbass is 30,605 hectares. Taking into account the discharge of pollutants both from the surface of the dumps and from the deflationary pollution zone, the area of such land is 35,765 hectares. The mathematical modelling of the processes of pollutant removal by wind and deposition on the soil surface showed that it is possible to radically reduce the area of pollution by afforestation of waste dumps and, first of all, their flat tops.

Keywords: coal mining, waste rock, erosion, deflation, soil pollution, afforestation.

1. Introduction

Coal reserves of coal are an important factor in the economic development of many countries. According to (The Coal Resource, 2005), nearly 40% of the world's electricity is generated using coal, and in many countries this figure is much higher: in Poland – over 94%; in South Africa – 92%; in China – 77%; in Australia – 76%. However, coal mining causes many environmental problems. Various aspects of the environmental hazards of coal mining are described in the works of scientists from many countries of the world: Australia and Germany (Zillig et al., 2015); Bangladesh (Mohammad et al., 2010); China (Zhengfu et al., 2007); India

(Pandey et al., 2014); Iran (Adibee et al., 2013); Poland (Gawor, 2014; Marcisz et al., 2021); Russia (Alekseenko et al., 2018); UK (Younger, 2004); Ukraine (Smirny et al., 2006; Yatsukh & Demchyshyn, 2009); USA (Chugh & Behum, 2014). Many of these problems are related to the accumulation of waste rock dumps in the mining area. For example, in Poland, coal mining waste are located on an area of more than 4000 ha in more than 220 dumps, where more than 760 million tonnes of waste have accumulated (Gawor, 2014). In China, about 4.5 billion tonnes of coal mining waste have accumulated in 1700 dumps, covering an area of 15,000 ha (Zhengfu et al., 2007). Since the beginning of coal mining in Ukraine, more than 1,000 waste dumps have been created, of which about 15–20% are burning.

The environmental impacts of active and abandoned coal mine dumps are caused by rock burning (Panov & Proskurnya, 2002), chemical leaching (Ribeiro & Flores, 2020), and catastrophic water and wind erosion (scouring and deflation) of the dump surfaces (Zubova et al., 2015). The consequences of entering of combustion, deflation and erosion products into the environment are: air pollution with gases (Younger, 2004, 2016) and dust (Chen et al., 2007; Rout et al., 2014), soil pollution (Rodríguez-Eugenio et al., 2018; Marcisz, 2021), water pollution (Belmer et al., 2014), changes in the chemical status of groundwater (Szczepańska-Plewa et al., 2010).

The interaction of pyrite-bearing rock with air and water has a great negative impact (Olías et al., 2016), leading to the formation of acid mine drainage (AMD) (Kusuma et al., 2012; Yucel & Baba, 2016). AMD is characterised by a lower pH, which favours the dissolution and leaching of lead and other heavy metals (HM) from both the mined rock (Ribeiro et al., 2020) and the waste dumps (Smirny et al., 2006). As a result of AMD, hydrochemical currents are formed from the dumps (Banerjee, 2014), leading to long-distance migration of contaminants (Zubov et al., 2019) and soil contamination. Contaminated soils contain Fe, Mn, Zn, Pb, Cu, Ni, Cd, Cr, and other elements above critical levels (Pandey et al., 2014; Manna & Maiti, 2018; Li et al., 2014).

The consequences of soil contamination with HM are its chemical degradation and reduction in quality (Guo et al., 2011; Pandey et al., 2014; Wuana & Okieimen, 2011) and, for agriculture in general, a reduction in land productivity (Kumar, 2013; Mishra & Pujari, 2005). The uptake and bioaccumulation of HM by food crops poses a risk to human health (Khan et al., 2015; Li et al., 2014) and to the countries' food security (Ocansey, 2013; Lu et al., 2015).

In view of the above, the objectives of the study were to develop a methodology for assessing the area of potentially contaminated land in the coal-mining regions and to determine the area of such land in Ukraine. In order to achieve the objectives of the study, the following tasks were solved: 1) to characterise the mechanism of land pollution during water and wind erosion of the dump surface; 2) to determine the current number of the dumps of different types in the Donbass and to characterise their morphometric parameters; 3) to assess the forest coverage of the dumps.

2. Materials and Methods

2.1. Study Area

The objects of study were all waste dumps of coal mine in Ukraine. The country's coal reserves are concentrated in the Donetsk and Lviv-Volyn coal basins (Fig. 1).

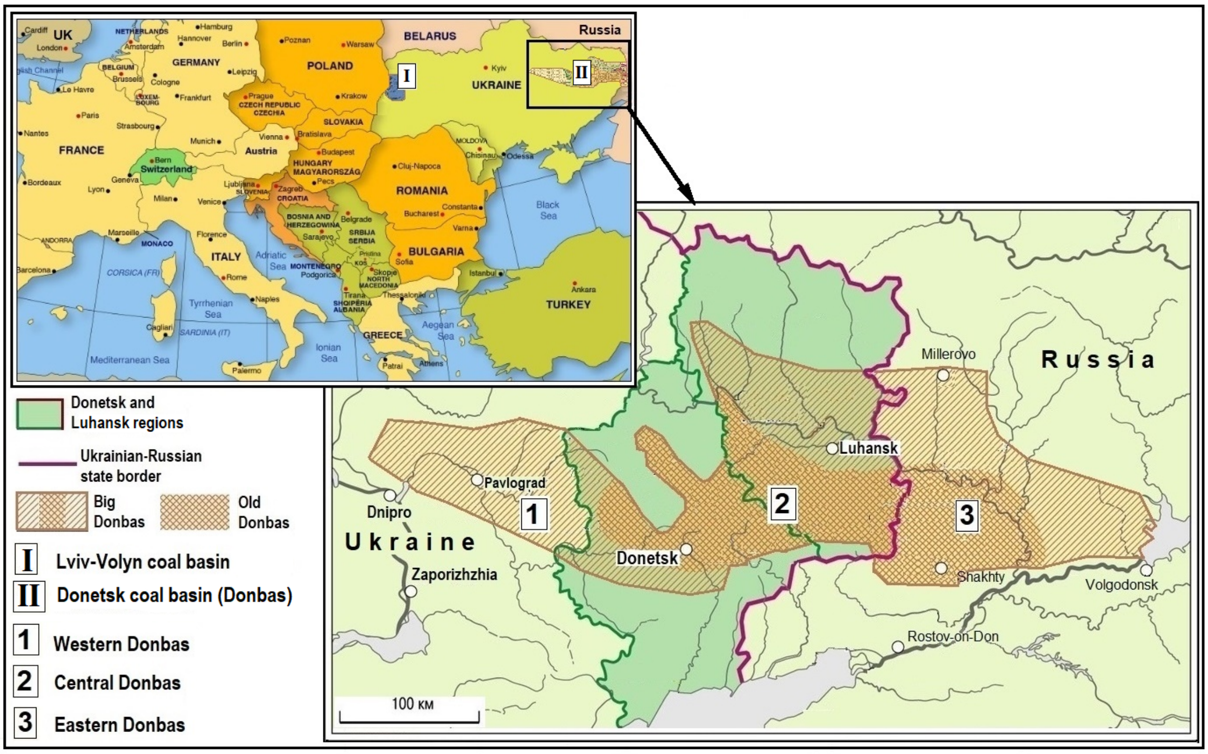


Figure 1. Location of the Donetsk and Lviv-Volyn coal basins.

The Lviv-Volyn coal basin covers an area of 3,200 km^2. According to Yatsukh and Demchyshyn (2009), there are 30 waste dumps here. The geographical extent of the area with them is between 50.29 – 50.79°N and 24.05 – 24.28°E. The area of the Donetsk coal basin (Donbass) is much larger – 60,000 km^2, its length in the latitudinal direction is 650 km, the maximum width is about 200 km (Plachkova et al., 2012).

The entire modern Donbass is called the Big Donbass, and its historical part is called the Old Donbass. The Big Donbass is divided into western, central and eastern parts (Fig. 1). Western Donbass is located east of the Dnipropetrovsk region, Central Donbass – in the Donetsk and Luhansk regions of Ukraine. Eastern Donbass is located in the Rostov region of

Russia.

There are 11 waste dumps in Western Donbass with a total volume of 100 million tonnes, covering an area of 200 ha (Petlovanyi & Medianyk, 2018). According to different sources, the number of dumps in Central Donbass (let's call it CD for short) varies from 1063 (Plachkova et al., 2012) to 1257 (Panov & Proskurnya, 2002). As we found out, the geographical extent of the area with dumps in CD is between 47.87 – 49.10°N and 37.00 – 40.00°E.

According to Panov and Proskurnya (2002), 74.3% of the waste dumps in the CD were formed by dumping rocks in a conical shape up to 50-100 m or higher, with a slope angle of up to 40º. Subsequently, many of the conical dumps were cut off at the top and became truncated cones. A smaller number of dumps were formed by dumping rock from dump trucks and levelling it with bulldozers, these are called flat dumps. In Ukraine cone dumps, and often other coal mine waste dumps are called *terricones*.

2.2. Data collection methodology

The baseline data for the waste dumps in the Donetsk region (let's call it DR) was provided by the Ukrainian Ministry of Energy's state-owned company 'Ukruglerestrukturizatsiya'. For the Luhansk region (LR) and Eastern Donbass, the research was carried out by analysing satellite images using the Google Earth service.

The height of the dumps was calculated as the difference between the average elevation of the flat top (plateau) and the foot of the dumps. Then the height was refined by the average slope projection length l' as the product $l' \times \mathrm{tg}\alpha$, where α is the slope angle, taken to be 35°. By subtracting the area of the dump plateau F_{pl} from the area of it's base F_b, the area of horizontal projection of the dump slopes F_{sl}' was calculated. The actual area of the slopes F_{sl} was calculated using the following equation: $F_{sl} = F_{sl}' / \cos\alpha$.

The volume of conical dumps was calculated using the equation: $V_d = F_b \times h_{av} / 3$.

The volume of truncated conical and flat dumps was calculated using the equation:

$$V_d = h_{av} \times [F_b + F_{pl} + (F_b \times F_{pl})^{0.5}] / 3.$$

Forest area on the slopes ($F_{f.sl}$) was determined as $F_{f.sl}' / \cos\alpha$, where $F_{f.sl}'$ is the horizontal projection of the $F_{f.sl}$. The forest coverage of the slopes and plateaus of the dump was determined as the ratio of the forest area on these elements to their area. The number of dumps was determined by careful search and recalculation.

The rock removal from the dump surface by wind and the area of contaminated land were determined using a mathematical model (Zubova et al., 2015) implemented in the form of Excel spreadsheets. To solve the tasks of this study, the model was improved. The initial calculation data are the height of the dump, the area of its base, the duration of winds with different speeds per year, and the fractional composition of the rock. The calculation resulted in plots of the mass of rock particles deposited per hectare (deposition density *d*, t/ha) versus distance from the dump centre.

3. Results and Discussion

3.1. Mechanism of pollution of the area due to erosion processes on the dump surface

An interpretation of the mechanism of pollutant dispersion from dumps and an algorithm for determining the area of pollution resulting from water erosion and deflation of the dump surface are proposed.

During rainfall and snowmelt (Fig. 2), runoff carries solid rock particles and dissolved substances from the slopes of the dump to its foot. According to (Zubova et al., 2015), approximately 90% of the removed rock is deposited at the foot of the dump. The presence of vegetation, various ditches and ramparts facilitates the accumulation process. However, fine rock particles ≤ 0.25 mm in size are able to migrate unimpeded with temporary water flows, carrying more than 100 kg/ha of HM from the dump surface annually.

The migration of pollutants is enhanced by the presence of hollows, which are the primary elements of the hydrographic network up to 1–2 m deep. According to (Zubov et al., 2009), on slopes of 1–3°, 3–5° and 5–7°, the distances between hollows are 150 – 260, 110 – 180 and 90 – 130 m apart, respectively. Runoff is concentrated in hollows, so solid and dissolved pollutants end up at the bottom of them. Some of pollutants settle in the soil, and some continue to move along the thalwegs of hollows to gullies and rivers.

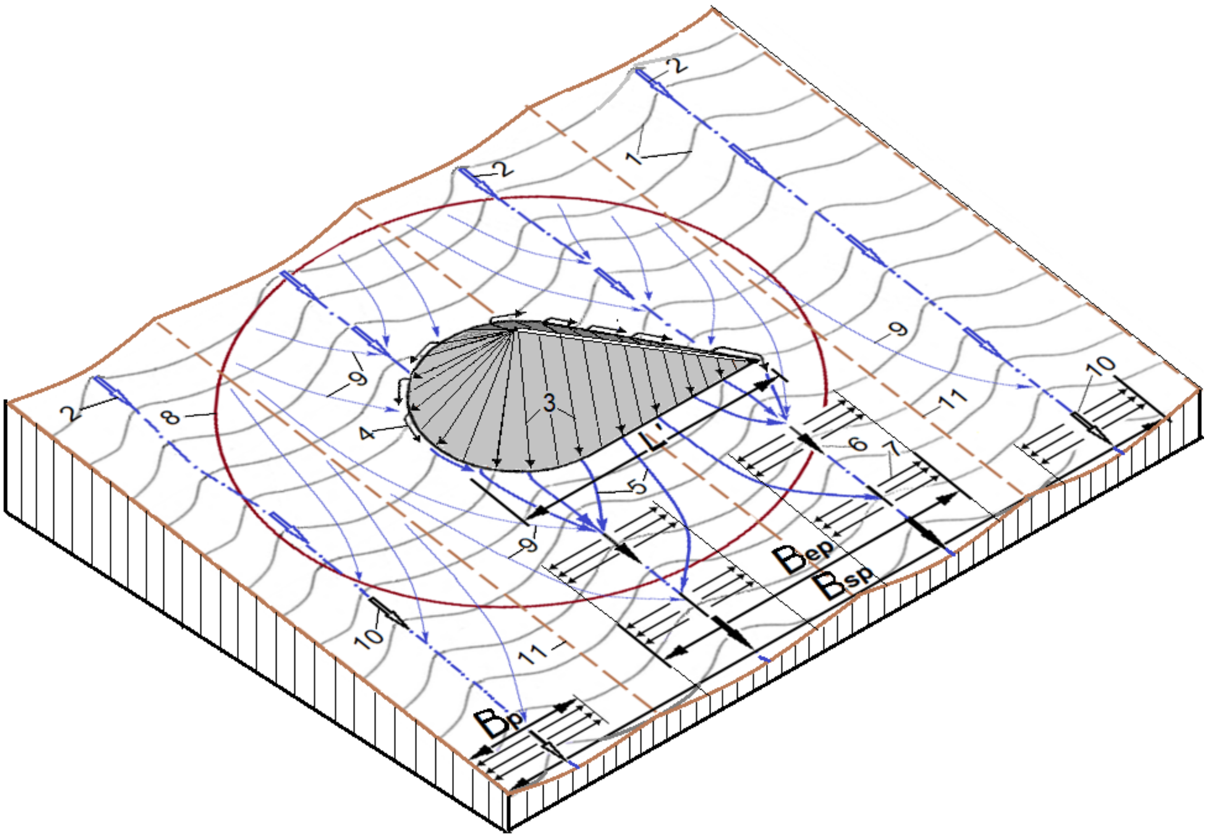


Figure 2. Scheme of the pollutants migration from a conical waste dump on the slope: 1 – contour lines; 2 – runoff of meltwater or rainwater from the upstream part of the slope along the thalwegs of the hollows; 3 – runoff of polluted water from the slopes of the dump; 4 – flows of polluted water along the foot of the dump; 5 – continuation of flows from the slope of dump to the field; 6 – flows of polluted water from the dump along the thalwegs of the hollows; 7 – lateral spreading of pollutants from the bottom of the hollows during the cultivation of the field; 8 – boundary of the zone of deflationary pollution; 9 – runoff from the zone of deflationary pollution; 10 – flows of polluted water from the zone of deflationary pollution along the thalwegs of the hollows; 11 – watersheds between the hollows.

When the soil is cultivated, its contaminated part spreads from the bottom of the hollow trough up to 20 - 30 m in both directions. This is confirmed by the results of soil analyses and the facts of the depressed state of agricultural crops below the investigated waste dumps (Zubova et al., 2015; Zubov et al., 2019). Thus, the erosion pollution zone (EP zone) has the appearance of a longitudinal slope consisting of several narrower strips of $B_{\mathrm{p}} \approx 50$ m width located in the hollows.

The length of the EP zone (L_{ep}) is the distance from the dump to the nearest gully or river. The width of the zone can be determined using equation (1):

$$B_{ep} = (n_h - 1) \times B_h + B_p, \tag{1}$$

where B_h is the average distance between the thalwegs of hollow within the EP zone;

n_h is the number of thalwegs to which the runoff flows.

The average number of hollows n_h within the EP zone depends on the ratio between the width B_h and the parameter L_b' (Table 1). This parameter is the projection of the dump base axis onto the perpendicular to the direction of the hollows (Fig. 3). The value L_b' can be calculated approximately as half the sum of the axis length L_b and the base width B_b.

Based on the inclination of the slopes of a typical conical waste dump α = 37° and the crest of its tail β = 19°, axis length $L_b = H_d \times (\mathrm{ctg}\alpha + \mathrm{ctg}\beta)$ = 210 m. The width of the base $B_b = 2H_d \times \mathrm{ctg}\alpha$ = 133 m. Therefore, the parameter $L_b' = 0.5 \times (L_b + B_b)$ = 167 m.

Table 1. The number of hollows n_h in the contaminated zone as a function of the ratio of the dump parameter L_b' and the width of the hollows B_b.

Intervals of the ratio L_b'/B_h	n_h	Intervals of the ratio L_b'/B_h	n_h
$L_b'/B_h \leq 0.5$	1.33	$3.5 < L_b' / B_h \leq 4$	4.67
$0.5 < L_b' / B_h \leq 1$	1.67	$4 < L_b' / B_h \leq 4.5$	5.33
$1 < L_b' / B_h \leq 1.5$	2.33	$4.5 < L_b' / B_h \leq 5$	5.67
$1.5 < L_b' / B_h \leq 2$	2.67	$5 < L_b' / B_h \leq 5.5$	6.33
$2 < L_b' / B_h \leq 2.5$	3.33	$5.5 < L_b' / B_h \leq 6$	6.67
$2.5 < L_b' / B_h \leq 3$	3.67	$6 < L_b' / B_h \leq 6.5$	7.33
$3 < L_b' / B_h \leq 3.5$	4.33	$6.5 < L_b' / B_h \leq 7$	7.67

We took the average distance between the hollows thalwegs B_h equal to 180 m. Comparing B_h and L_b', we found that $0.5 < L_b' / B_h \leq 1$, therefore n_h = 1.67. According to equation (1), the width B_{EP} of the polluted zone EP is 171 m. The average length L_{EP} of the EP zones of a group of waste dumps can be defined as half the length of the catchment slope on which the dumps are located. According to our calculations, the length of the catchment area slope of dry valleys or small rivers in the Central Donbass is 750 m on averages, and its half is 375 m. According to (Zubova et al., 2015), the base area F_b of a typical waste dump can be expressed in terms of the radius R_b of its frontal part or the height H_d according to the empirical equation: $F_b = 3.99 \times R_b^2 = 7.03 \times H_d^2$ m^2. In the case under consideration H_d = 50 m, F_b = 1.76 ha, and the area of the pollution zone $F_{EP} = L_{EP} \times B_{EP}$ = 5.53 ha.

During deflation of the dumps surface, the rock is removed in all directions during the year, therefore, a circular zone of deflationary pollution (DP zone) is formed near the dump.

As a result of experiments with the developed laboratory aerodynamic plant (Patent No. 53815, Ukraine) and application of a complex of developed algorithms (Zubova et al., 2015), the authors earlier found that the potential average multi-year removal of rock from the waste dump surface due to deflation is almost 150 t/ha yr^{-1}. The intensity of rock deposition at the foot of the dump (lets call it deposition density d_P) reaches tens of t/ha yr^{-1}, but decreases sharply with distance from the dump.

Consider an example of the implementation of an algorithm to determine the area of the DP zone for a conical dump with a height H_d equal to 50 m. Using the developed mathematical model, the radius of the circles with d_{DPi} = 1, 5 and 10 t/ha yr^{-1} were determined: R_{DP1} = 225 m, R_{DP5} = 138, R_{DP10} = 112 m.

The area of the DP zone, excluding the dump base area F_b, can be expressed as $F_{DP} = \pi \times R_{DPi}^2 - F_b$. With R_{DP1} = 225 m, F_{DP} = 14.15 ha. The contaminated area thus exceeds the base area of the waste dump by 8 times.

The total area of the zone polluted by deflation and water erosion (DEP zone) $F_{DEP} = F_{DP} + F_{EP}^{II}$, where F_{EP}^{II} is the area of the part of EP zone that extends beyond the zone DP (as will be shown later in Fig. 8). The calculation of F_{EP}^{II} is similar to the calculation of F_{EP} (paragraph 3.1.1), but the radius of the DP zone R_{DP1} = 225 m should be subtracted from L_{EP}. Thus, $F_{EP}^{II} = B_{EP} \times (L_{EP} - R_{DP1})$ = 2.57 ha, F_{DEP} = 16.71 ha.

The part of the *EP* zone within the *DP* zone (let's call it EP^{I}) is subject to both erosive and deflationary pollution and is therefore the most environmentally dangerous. The area of this part $F_{EP}^{I} = F_{EP} - F_{EP}^{II}$ = 2.97 ha.

By subtracting the area of EP^{I} zone from the area of DP zone, we determined the net area of the deflationary pollution zone DP_{NT}: $F_{DPnt} = F_{DP} - F_{EP}^{I}$. The area of the DEP zone can also be calculated using the eguation: $F_{DEP} = F_{DPnt} + F_{EP}$.

Under influence of runoff from the soil surface, contaminated because of deflation of the waste dump surface, there is an additional removal of HM into the hollows. It is important to note that this also occurs in hollows that are not hydrologically connected to the heap (Fig. 2). Therefore, the width of the EP zone increases from B_{EP} to B_{SP} (Fig. 2). Taking into account the zone of additional erosive pollution (conditionally ΔEP^{II}), the area of the EP^{II} increases by $F_{\Delta EP}^{II} = (B_{SP} - B_{EP}) \times (L_{EP} - R_{DP1})$. The ΔEP^{II} zone differs from the EP^{II} zone by a significantly lower inflow of pollutants, however, with a strict approach to assessing the area of pollution, it should also be taken into account.

To determine the B_{SP}, the parameter L_b'' should be used instead of L_b'. The parameter L_b'' is the doubled radius R_{DP} of the DP zone for a given deposition density d_P.

As the calculation shows, if $L'' = 2R_{DP5}$ = 276 m, then $1.5 \leq L_{10}''/B_h \leq 2$, and n_h = 2.67. The width of the contamination zone B_{SP10} according to equation (2) is 351 m. As the calculation has shown, for a typical conic dump, $F_{\Delta EP}^{II}$ = 2.69 ha. Therefore, the total pollution area increases from F_{DEP} = 16.71 to $F_{DEP}' = F_{DEP} + F_{\Delta EP}^{II}$ = 19.40 ha.

In order to implement the algorithm for calculating the pollution from a large group of dumps, it is necessary to know their quantity, the distribution of the dumps over height intervals, the average base area and the tops of the dumps for each interval.

3.2. Typology, quantity and morphometric indicators of dumps

The analysis of the space images of all waste dumps of LR made it possible to obtain the following classification of dumps by shape and location (Table 2, Fig. 3-5).

Table 2. Developed classification of dumps.

Types (I-III) and subtypes of dumps (a, b, c)		
I. Conical	II. Truncated conical	III. Flat
a) single (Fig. 3)	a) single (Fig. 3)	a) bulk single-tier
b) radially divergent (Fig. 4)	b) radially divergent	b) bulk multi-tier stepped (Fig. 6)
c) paired and triplets with a common base	c) paired, with a common apex (Fig. 5)	c) formed from a truncated by significant downgrading and reshaping

The total number of coal mine waste dumps in the Donetsk region was determined to be 596. Of these, 169 (28.3%) are burning. For each type of dump, the number, average height, area and volume were calculated (Table 3).

Table 3. Number and average indicators of dumps in the Donetsk region.

Dump type	Quantity		Height H, м	Base area F_b, ha		Volume V_d, million m^3	
	pc	%		average	total	average	total
I	314	52.5	48.6	3.8	1170	1.05	318.0
II	102	17.1	44.1	5.2	540	1.53	154.3
III	180	30.4	35.9	10.4	1828	3.22	573.5
In sum	596	100			3533		1044.8

Note: I - conical dumps; II - truncated conical dumps, III - flat dumps.

Figure 3. Conical and truncated conical rock dumps (Lysichansk sity)

Figure 4. Conical radially divergent dumps No. 2 and 3 of the ‘D.F. Melnikov’ mine – one of the field studies sites (geographical coordinates: 48°54.82'N and 38°23.09'E).

Figure 5. ‘Matrosskaya’ mine's paired truncated-conical dumps with a common top – one of the study sites (48°50.89'N and 38°25.88'E) and soil contamination down the slope.

Figure 6. Flat bulk multi-tiered stepped dump of the ‘Yubileynaya’ mine – the object of previous field studies (geographical coordinates: 48°31.46’N and 39°10.14’E).

The total number of dumps in the Luhansk region is 694. Of these, 219 (31.6%) are conical (including 16 double or triple dumps), 289 (41.6%) are truncated conical (including 8 double or triple dumps), 186 (26.8%) are flat. The randomized sample of 234 dumps was formed from all the dumps. After determining the parameters of each dump, their average values were calculated: height H_{dav}, m; base area F_{bav}, ha; flat top area $F_{p.av}$, ha; slope area $F_{sl.av}$, ha; total surface area F_{sum}, ha; perimeter of dump base $P_{b.av}$, km; dump volume $V_{d.av}$, million m^3 (Table 4).

Table 4. Averaged indicators of a sample from the dumps in the Luhansk region.

Dump type	Quantity		$H_{d.av}$, м	F_{bav}	Surface area, ha			P_o, km	V, 10^6 m^3
	units	%			$F_{p.av}$	$F_{sl.av}$	F_{sum}		
I	76	32.3	47.4	2.87	-	3.50	3.50	0.58	0.552
II	87	37.1	30.5	3.07	0.74	2.85	3.59	0.62	0.606
III	72	30.6	35.5	8.60	2.99	6.92	9.91	1.16	2.886
Total	234	100		1104.4	280.0	1012.0	1292.0	181.7	302.5

Note: I – conical dumps; II – truncated conical dumps, III – flat dumps.

Based on the share of dumps of each type of sample from their number in the general population and the data in Table 4, it can be concluded that the area under all 694 dumps in LR and their volume are 2495 ha and 832.8 million m^3, respectively, and the total base perimeter is 522.4 km. In sum with the DR indicators (Table 3), the area under dumps and their volume in the all Central Donbas amount to 6028 ha and 1.876 billion m^3. The number of the dumps in the Central Donbas is 1290.

We have calculated that the number of dumps of coal mines in the Eastern Donbass is 299. Among them there are 98 cone, 107 truncated cone, 91 flat and 3 ridge dumps. The average height of the conical, truncated conical and flat dumps is 28.7, 20.5 and 15.5 m respectively. Together with the dumps of the Western and Eastern Donbass (11 and 299 respectively), the number of dumps in Big Donbass is 1,600.

The assessment of the actual forest cover of dumps is presented in Table 5.

Table 5. Average forest cover of different types of dumps in Luhansk region.

Dump types	Dump elements and planting area on them					
	Top		Slopes		Whole surface	
	ha	%	ha	%	ha	%
I	-	-	0.69	23.6	0.69	23.6
II	0.15	19.1	0.58	22.6	0.73	21.9
III	0.14	14.7	0.64	20.1	0.83	18.8

For a more detailed description of the dumps, we determined the distribution of their number over the intervals of the range of variation of their height as a percentage of the total number (Table 6).

Table 6. Distribution of dumps in the Central Donbass by height (as %).

CD regions	dump type	Height intervals, m									
		<10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	>90
DR	I	3.2	11.4	12.7	**15.3**	14.8	13.3	11.4	8.8	5.5	3.6
	II	5.8	8.7	13.5	11.5	**23.1**	20.2	8.7	6.7	1.9	0.0
	III	8.7	16.4	18.0	**21.3**	10.9	9.8	9.3	2.7	2.2	0.5
LR	I	1.5	6.0	14.9	**22.4**	14.9	17.9	13.4	0.0	3.0	6.0
	II	6.3	23.8	**32.5**	13.7	12.4	3.8	5.0	2.5	0.0	0.0
	III	8.5	18.6	**23.7**	**16.9**	6.8	6.8	6.8	6.8	1.7	3.4

The average values of the base area F_b and other dump parameters were determined for each height interval of the dumps of the Central Donbass. It was found out that many parameters of dumps correlate well with the length of their base axis, which allows to simplify the determination of these parameters. Thus, the relationship between the area of the base of type I, II, III dumps and the length of their axis is expressed by the equations:

$$F_{b\mathrm{I}} = 7\cdot10^{-5}L_b^{1.94};\ F_{b\mathrm{II}} = 7\cdot10^{-5}L_b^{1.94};\ F_{b\mathrm{III}} = 0{,}0002L_b^{1.82} \quad (2)$$

The coefficients of determination R^2 of the relationships are 0.92; 0.86; 0.87.

The base area of the dumps correlates even better with the product *Lb and Bb*:

$$F_{b\mathrm{I}} = 0.76L_bB_b;\ F_{b\mathrm{II}} = 0.72L_bB_b;\ F_{b\mathrm{III}} = 0.72L_bB_b \quad (3)$$

($R_{\mathrm{I}}^2 = 0.97$; $R_{\mathrm{II}}^2 = 0.93$; $R_{\mathrm{III}}^2 = 0.81$ respectively).

The relationship between the width and length of the dumps' base is determined by the following equations: $B_{b\mathrm{I}} = 0.743L_b$; $B_{b\mathrm{II}} = 0.725L_b$; $B_{b\mathrm{III}} = 0.655L_b$). (4)

(R^2 = 0.85, 0.72, 0.82 respectively).

On the basis of equations (3, 4), empirical equations were derived to determine the parameter L' for each type of dumps:

$$L_{\mathrm{I}}' = 1.164\cdot F_b^{0.5},\ L_{\mathrm{II}}' = 1.19\cdot F_b^{0.5},\ L_{\mathrm{III}}' = 1.193\cdot F_b^{0.5}. \quad (5)$$

Using a previously developed mathematical model, plots of changes in the density of annual deflationary pollution as a function of the distance RDPi from the centre of the dumps were drawn for three types of landfill with heights of 10, 20 ....10 m (Fig. 7).

Then the distances from the centre of the dumps to the circles with pollution density d = 1, 5, 10, 30, 50 t/ha yr^{-1} were taken from the graphs and equations of dependence of R_{DPi} on a given d t/ha yr^{-1} and a given height of dumps of each type were obtained (R^2 of all dependences are not lower than 0.98).

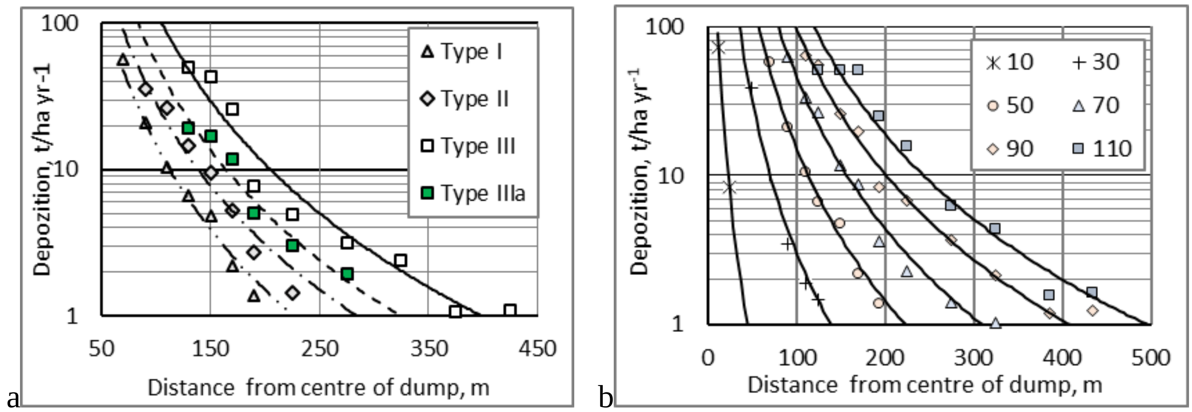


Figure 7. Examples of the dependence of the deflation density on the distance from the centre of cone dumps of different heights (a) and different types of medium height dumps: type I (h_{dav} = 50 m), type II (h_{dav} = 34 m), type III (h_{dav} = 36 m), type III' - the same, but without considering the deflation on the plateau in case it is fully afforested (b).

In the Luhansk region, for Type I dumps: $R_{DP} = 4.494d^{-0.302}H_d$;

Type II: $R_{DP} = 5.272d^{-0.334}H_d + 84.5d^{-0.227}$; Type III: $R_{DP} = 6.62d^{-0.273}H_d + 156.6d^{-0.213}$.

In the Donetsk region, for Type I dumps: $R_{DP} = 4.49d^{-0.302}$;

Type II: $R_{DP} = 6d^{-0.332}H_d + 110.4d^{-0.286}$; Type III: $R_{DP} = 6.936d^{-0.235}H_d + 115.2\ d^{-0.125}$.

According to the equations, the values of R_{dp1}, R_{dp5} and R_{dp10} for dumps of different heights and types were determined for circles with pollution levels d = 1, 5 and 10 t/ha.

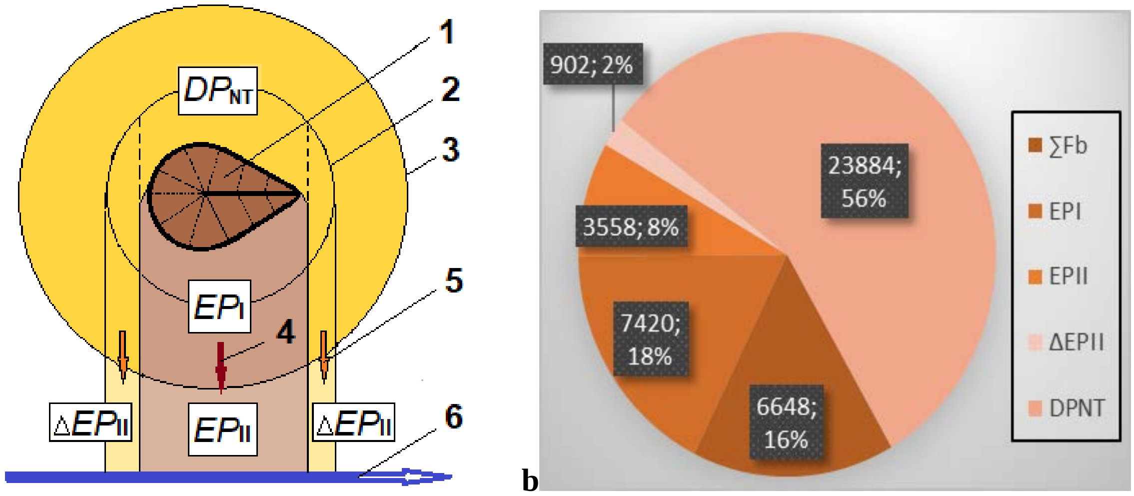
Knowing the number of dumps of each type in each interval of their height, the average values of dumps base area, we calculated the values of the parameters L', R_{DPi}. Then, using the algorithms described in subsection 3.1, we determined the area of all types of polluted zones for each type of dumps, regions and the whole Central Donbas (Table 7).

Table 7. Calculation of the area of polluted lands due to water and wind erosion of the surface of dumps in the Central Donbass (ha).

Region	Dump types	$\sum F_b$	Pollution zones and their areas						
			DP	EP	EP_{II}	EP_I	DP_{NT}	ΔEP_{II}	DEP'
Luhansk	I	633	2993	1660	763	896	2097	172	3928
	II	870	5082	2389	934	1456	3626	324	6340
	III	1690	9083	1804	246	1559	7524	100	9429
In sum		3193	17158	5853	1943	3911	13247	596	19697
Donetsk	I	1180	4244	2432	1111	1321	2923	170	5525
	II	434	2850	912	195	717	2133	24	3069
	III	1521	7053	1781	309	1472	5581	111	7473
In sum		3135	14147	5125	1615	3510	10637	305	16067
All CD		6648	31305	10978	3558	7420	23884	902	35765
On average for each dump		5,15	24,27	8,51	2,76	5,75	18,52	0,70	27,72

The reciprocal location of the waste dump and the DP_{NT}, EP_I, EP_{II}, ΔEP_{II} zones that make up the DEP' zone, which has an area of 35765 ha, is shown in Figure 8a.

Together with the dump bases, the contaminated area in Central Donbass, designated as DEP", is 42413 ha. The areas of the contaminated zones and waste dumps in hectares and as a percentage of the DEP" area are shown in Figure 8b. As can be seen, the area occupied by all 1,290 dumps (∑Fb) is 16% of DEP". Thus, the total area of contamination is 5.3 times the total area of waste dumps and 56% of it is due to deflationary contamination.



a b

Figure 8. Scheme of the location of zones of different pollution types (a) and diagram of the ratio of their areas (b). Note: 1 – dump; 2 – boundary of deflationary pollution subzone DP_5 with annual pollution level $d_P > 5$ t / ha yr; 3 – boundary of deflationary pollution zone DP with $d > 1$ t / ha yr; 4 – direction of pollutants in EP zone; 5 – direction of pollutants from DP into ΔEP_{II} zone; 6 – river valley or dry valley.

It was determined that the surface area of all dumps of CD subjected to erosion is 8013 ha. As mentioned above, from each hectare of dump surface area, about 100 kg of HM in mobile form enters the environment with runoff. Therefore, from all dumps, 801 tons of HM or more than 70 kg ha^{-1} per year enter the EP zone with an area of 10,978 ha.

The most dangerous subzone is EP_{II}, located below the slope dump, which is subject to both water erosion and deflationary pollution. On average, each waste dump contaminated 27 ha of land. This area corresponds to a circle with a radius of 1,055 m, which is consistent with data (Alekseenko et al., 2018) that in the Donbass the air-water migration of material from dumpsites changes soil properties within a radius of 1 km.

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Land contamination poses a great danger to the population, as many waste dumps are located in or near cities. Near the dumps are arable land, homestead plots and vegetable gardens, from which the local population obtains contaminated food for own consumption.

As shown in Table 3, flat dumps account for 28.3% of all dumps, but they pollute about 48% of all contaminated land. As Table 4 shows, the proportion of the top of flat dumps is about 30% of the total area of the surface of the dumps. If the top of the dump is completely forested, the deflation stops here. Therefore, its area can be disregarded in the calculation of the deflationary pollution of the area with the waste dumps. As shown in Figure 8 (line III'), in this case the pollution density at the foot of a typical 36 m high flat landfill decreases from 50 to 20 t ha-1, the RDP1 radius of the DP zone decreases from 395 to 328 m.

This result indicates the importance of afforestation of the dumps and especially of their tops. As shown in Table 7, on average only 14.7% of area of the flat dump tops are covered by forest. Approximately 36, 47 and 61% of type I, II and III dumps are forested less than 10%. As the authors' experience with afforestation of the PJSC "Lisichanskcoal" dumps (Zubova et al., 2015) and observations on other dumps show, afforestation not only protects the surface from deflation. It increases the permeability of the rock, radically reduces runoff, stops erosion processes and pollution of the territory.

The value of the total width of erosive pollution zones B_{SP}, equal to 435.7 km, allows us to estimate the length of sections of dry valleys and rivers that are subject to pollution and need protection. Since hollows are the main route of pollutant migration in the landscape, it is possible to prevent the spread of pollutants from the bottom of hollows on arable lands by grassing the bottom and slopes of hollows. Like reforestation, this is one of the most important tools for managing environmental safety in an area with coal mine waste dumps.

4. Conclusion

As a result of the recalculation on the basis of satellite images, the exact modern number of coal mine waste dumps in the central part of Donbass (Central Donbass), located inside Ukraine, and in the eastern part of Donbass, located in the Russia, was determined – 1290 and 299 units respectively. Taking into account the western part (11 units), the total number of dumps in Donbass is 1600. Taking into account the Lviv-Volyn basin (30 units), there are 1331 coal mining waste dumps in Ukraine. The total area occupied by dumps in central Donbass and their volume are 6,028 ha and 1.878 billion m^3. These figures and the morphometric indicators of the dumps – height, base area, area of plateau and lateral surface – are important for assessing both the hazard of the dumps and the possibility of using them.

The developed methodological approach made it possible to determine that the total area of land potentially contaminated by the deposition of the waste rock particles in the Central Donbass is 31,305 ha. Taking into account the removal of particles by water erosion, an additional 3558 ha is contaminated. Surface runoff from the zone of deflationary pollution increases the area of pollution by another 902 ha to 35765 ha. More than 7400 ha are subject to deflationary and erosion contamination together. Almost 50% of the pollution comes from flat waste dumps. The area of dumps exposed to erosion and deflation is 8013 ha.

The protective role of natural and man-made woody vegetation is low, as 36, 47 and 61% of type I, II and III dumps are less than 10% forested. Thus, in the coal-mining regions of Ukraine there is a significant reserve for reducing environmental hazards through afforestation of waste dumps of coal mines.

The developed methodical approaches can be used when designing engineering-biological measures on the area with waste dumps to protect soils from contamination and to determine restrictions on the cultivation of certain agricultural crops.

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