GIS-BASED CATCHMENT SCALE MODELLING OF TOXIC METAL TRANSPORT BY EROSION IN AN ABANDONED MINING AREA

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Summary

GIS (Geographical Information System) based catchment scale modelling of the risk of toxic metals by solid erosion through water (runoff) and the estimation of the pollutant transport is presented in this paper. The work is part of an environmental risk management methodology for mine waste and abandoned mining sites and this study covers risk assessment and risk reduction planning in a base metal sulphide ore mining area, in the Toka creek watershed of Gyöngyösoroszi, NE Hungary. The studied area includes point and diffuse pollution sources of mining origin (mine waste dumps, flotation tailings dump, lime precipitate from acid mine drainage treatment). The highest environmental risk is represented by the base metal sulphide containing non-vegetated mine waste dump surfaces exposed primarily to erosion through runoff. The GIS-based catchment scale pollution transport model was developed, based on the flow accumulation and erosion model. The GIS work on the runoff water transported dissolved pollution was published in 2005. 2006 [5] [5a] and 2007 [6] and was extended to the runoff transported solid phase.

This paper presents the GIS (Geographical Information System) based catchment scale modelling of the risk of erosion through runoff and solid transport, as part of an environmental risk management methodology. The GIS-based approach was integrated into a three tiered iterative risk assessment methodology, including 1. the qualitative risk assessment, 2. quantitative hazard due to emission and site-specific quantitative risk assessment tiers. Soil erosion model was based on the Revised Universal Soil Loss Equation (RUSLE) methodology, using the GRASS 5.4 software. The output data of the model provided data on metal emission for Environmental Hazard Assessment. As part of our risk management methodology, we planned the necessary emission reduction by remediation. Considering the typical erosion of the local forest area, our target was to reach at least this erosion level on the waste dump area to fulfil 99.7% emission-reduction and a no risk situation. The suitable technology for this target was the combined chemical and phytostabilisation, demonstrated and confirmed on site through field experiments (see poster theme “E”: Feigl, V. et al.: Combined chemical and phytostabilisation of metal polluted soils – From microcosms to field experiments).

Introduction

Waste from current and abandoned extractive operations (i.e. waste from extraction and processing of mineral resources) is one of the largest waste streams in the EU. Waste generated by the non-ferrous metal mining industry, may contain large quantities of dangerous substances, such as toxic metals. Through the extraction and subsequent mineral processing, metals and metal compounds tend to become chemically more available, which can result in the generation of acid or alkaline drainage. A comprehensive framework for the safe management of waste from extractive industries at EU level, Directive 2006/21/EC of the European Parliament and of the Council on the management of waste from the extractive industries, is now in place [13]. Base metal and coal mining activity in Hungary started to get slowly reduced from 1985, however the abandoned base metal and coal mining and extraction sites represent major pollution sources. Mine closure, rehabilitation and remediation project works have been and are being in progress in Hungary. For this reason the management of point and diffuse pollution of mining origin is a one of the major topics of our work.

Erosion through water affects large areas of abandoned mining sites and is responsible for the largest transport of solid mine waste, causing reduced water and soil quality. The regional and catchment scale soil erosion has a significant spatial and temporal variability. Quantitative assessment is almost impossible based on direct measurements [1]. The increasing availability of regional scale data layers on climate, topography and land use has recently led to the application of quantitative soil erosion

models. The models are relatively successful in predicting the relative pattern of solid transport at catchment or regional scale [1].
Two risk scenarios were studied in the mine waste dump area of the Northern catchment of Toka creek: 1. erosion through average intensity rain, 2. erosion through high intensity rain. The average annual transported solid waste per area (t/year/ha) was assessed in the above two cases as minimum and a maximum erosion cases.

Location of the studied area

The studied area is located between the 708342,279010 – 712955,283778 EOV coordinates in the Northern catchment of the Toka creek, upstream to the Altáró adit in Gyöngyösoroszi, NE Hungary. The elevations are ranging from 330 to 824 meters. A 2,5 m resolution DTM (Digital Terrain Model) was produced for the area. The high resolution was necessary in order that our study covers several small size waste dumps. The forests dominate mostly in the area. In Figure 1 the studied watershed area is delineated with dark green and the mine waste dumps with pink colour.

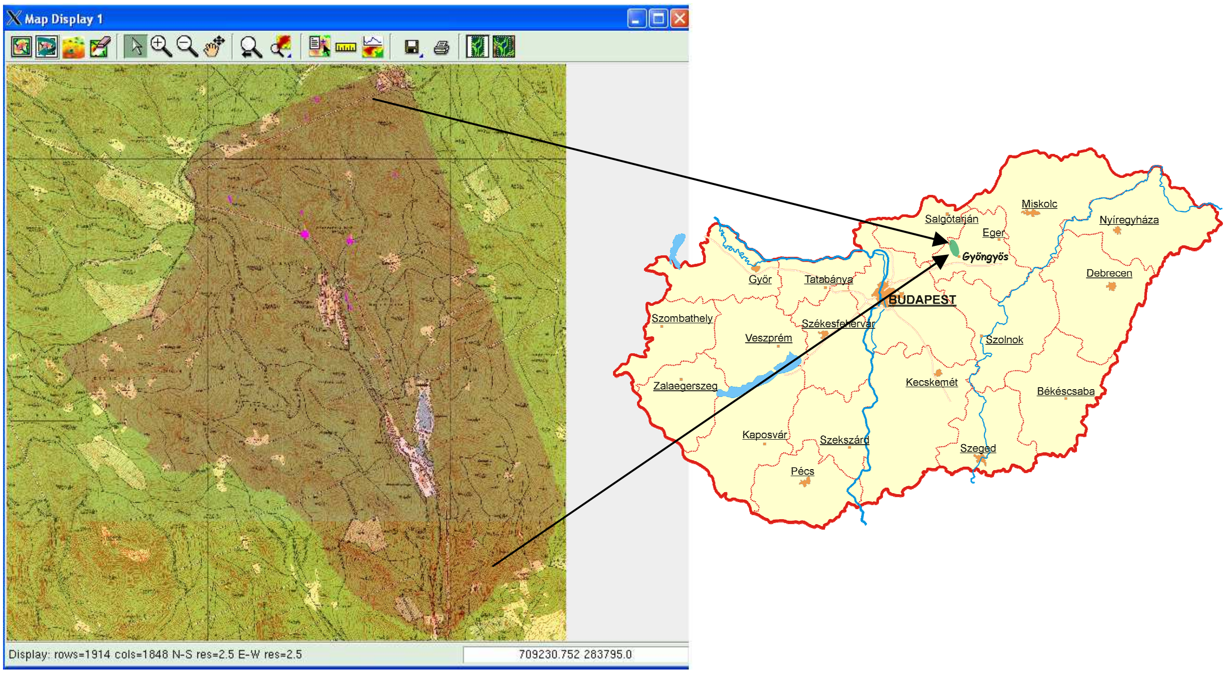

Figure 1 Location of the delineated watershed and mine waste dumps in Gyöngyösoroszi, Hungary

Soil erosion modelling

Soil erosion modelling was done with the GRASS 5.4 (http://www.grass.itc.it) software. The model was based on the Revised Universal Soil Loss Equation (RUSLE) A= R*K*L*S*C*P methodology [7, 11]. The RUSLE equation quantifies the soil erosion as the product of six factors representing rainfall and runoff erosivity (R), soil erodibility (K), slope length (L), slope steepness (S), cover and management practices (C), and supporting conservation practices (P). The equation is thus: A = R*K*L*S*C*P, where A is the computed spatial and temporal average soil loss per unit of area [7]. Only two of the six factors in the equation, the rainfall and runoff erosivity factor (R) and the soil erodibility factor (K), have units. The average annual soil loss per unit of area is expressed in the units selected for K and the period selected for R [11].

Average annual soil erosion rates (A) (in t.ha-1.yr-1) were assessed by multiplying 6 different factors: rainfall erosivity factor (R), a soil erodibility factor (K), a topographic factor (LS), land cover and land use factor (C) and soil protection factor (P). These factors were assessed at 2.5 m resolution using 20 years average rainfall data [9] CORINE Land Cover data [3], flow direction, slope and Flow Accumulation map developed from the Digital Terrain Model (DTM) [6]. The erosion rates were classified in 5 classes. The erosion map was produced based on the quantitative output ranges. The predictable As, Pb and Cd, Cu Zn emission of the soil/waste eroded from the Northern catchment of Toka creek and solely from the mine waste dump area was modelled according to the pollution levels (minimum and maximum), rain (average and heavy) and soil conditions typical for the area.

Calculation of the RUSLE parameters

The calculated Rusel-parameters are: rainfall and runoff erosivity (R), soil erodibility (K), slope length and steepness factor in raster GIS (LS), cover management factor (C), support practice factor (P)

Rainfall and runoff erosivity (R)

R is the rainfall erosivity index that represents the energy that initiates the sheet and rill erosion. It is a function of kinetic energy. In this research the rainfall factor was computed from the following empirical relationship [11]: R = 0.1059*a*b*c + 52.0, where a = average annual rainfall (cm); b = maximum 24 hours rainfall with a return period of 2 years (cm/24hours); and c = one hour maximum rainfall with recurrence interval of 2 years (cm/hour) [11]. The average annual rain used in the equation is the 20 years monthly average of the Matra area measured by the Hungarian Meteorological Service (**756 mm/year)** [9]**.** The rain intensity (b, c) was read from the rain gauge in the Gyögyösoroszi mine yard [6].

Two cases were studied: low intensity rain (A) and heavy intensity rain (B).

A case
a = 75.6 cm
b = 7.4 cm/24 hours
c = 1.8 cm/hour
R=~160 t/ha/year

B case:
a = 75.6 cm
b = 10.5 cm/24 hours
c: = 5.3 cm/hour
R=~500 t/ha/year

In case of heavy intensity rain the erosivity is three times the erosivity of the low intensity rain**.**

Soil erodibility (K)

K is the soil erodibility index referred to as mean annual soil loss per unit of R for a standard condition of bare soil, recently tilled up-and-down slope with no conservation practice and on slope of 50 and 22m length. Soil erodibility is related to the integrated effect of rainfall, runoff, and infiltration. From different available literature [the following K value for different soil types was established.

Table 1 Soil Type Erodibility Factor

	Soil type	**Erodibility Factor K**
1	sand, cobbly	0.1
2	sandy	0.12
3	variable	0.12
4	loamy	0.23
5	loamy, boulder	0.20
6	loamy skeletal	0.23
7	fragmental sand	0.10

In this study the erodibility factor (K) for forestry areas is 0.12 and for the mine waste dumps it is 0.23.

Slope length and steepness factor in raster GIS (LS)

The concept of replacement of slope length with up slope drainage area per unit of contour length was applied. With this substitution each of the grid cells within the DEM is considered as a slope segment having uniform slope. The LS was created with the command r.wastershed and this command created LS factor directly. The calculated LS factor should be divided by 100 to convert as real LS factor [11].

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+-----------------------------------------------------------------------+
|             Category Information             |    square|          |   cell|
|            #|description                     |    meters|  hectares|  count|
|-----------------------------------------------------------------------|
|    0.03-1.763|from  to . . . . . . . . . . . . | 8,128,175| 812.81750|1300508|
|   1.763-3.496|from  to . . . . . . . . . . . . | 1,537,588| 153.75875| 246014|
|   3.496-5.229|from  to . . . . . . . . . . . . |   577,656|  57.76562|  92425|
|   5.229-6.962|from  to . . . . . . . . . . . . |   218,831|  21.88312|  35013|
|   6.962-8.695|from  to . . . . . . . . . . . . |    89,338|   8.93375|  14294|
|  8.695-10.428|from  to . . . . . . . . . . . . |    38,844|   3.88438|   6215|
|10.428-12.161|from  to . . . . . . . . . . . . |    20,806|   2.08062|   3329|
|12.161-13.894|from  to . . . . . . . . . . . . |      6031|   0.60313|    965|
|            *|no data. . . . . . . . . . . . . |11,489,431|1148.94313|1838309|
|-----------------------------------------------------------------------|
|TOTAL                                         |22,106,700|2210.67000|3537072|
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Cover management factor (C)

C is the cover management factor, which represents the ratio of soil loss under a given crop to that from bare soil. According to RUSLE the C factor should be calculated from the equations, as follows:

C = PLU*CC*SC*SR*SM

PLU – prior land use; CC – canopy cover; SC – surface cover; SR – surface roughness; SM –- soil moisture

In our study the following C values were used: forest area: 0.01, mine waste dumps: 0.8. The CORINE [3] and cover map was the basis for establishing the C value. Figure 2 shows the CORINE land cover map [3] of the Toka watershed and Figure 3 the landuse map of the studied Northern Toka watershed according to the calculated C values.

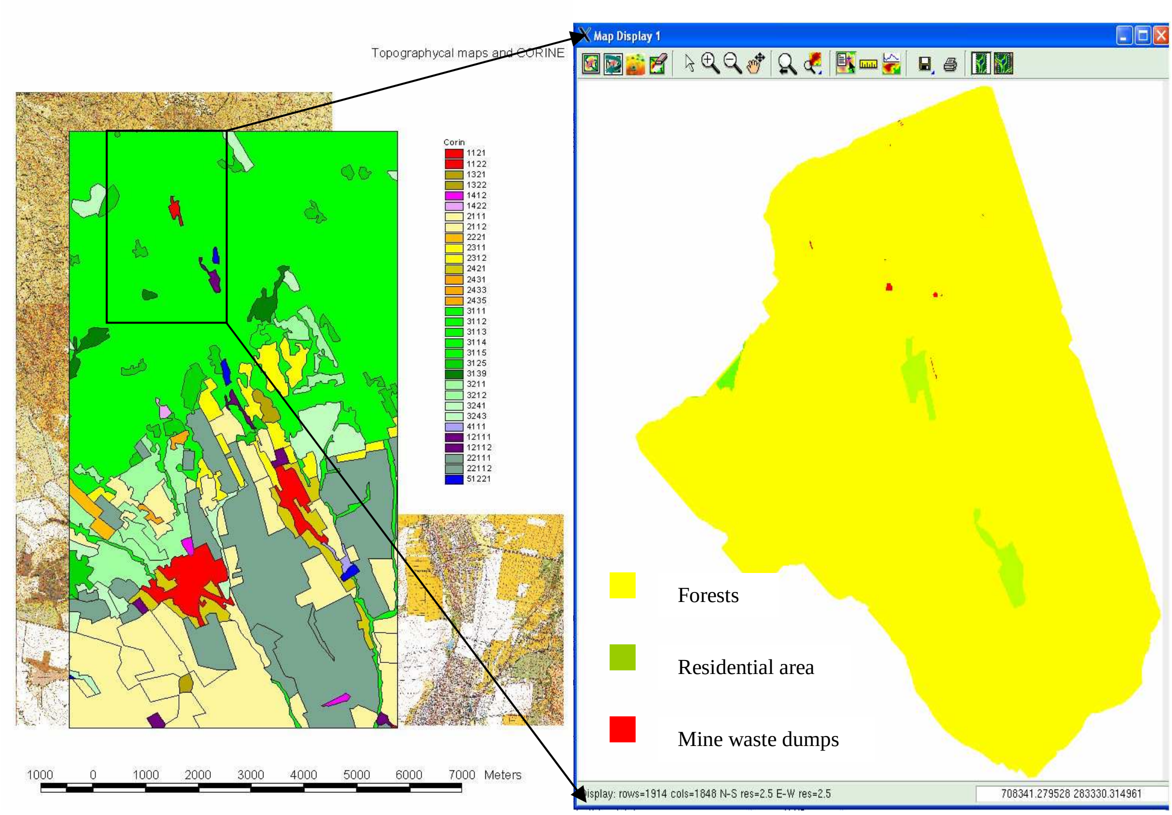

Figure 2 CORINE landcover map

Figure 3 Reclassified landcover map

Support practice factor (P)

The support practice factor "P" in RUSLE is the ratio of soil loss with a specific support practice to the corresponding loss with up and down slope tillage, which has a value of 1.0 [11] [12].

Potential Solid Material Loss Calculation

The annual solid material loss (tonnes/ha/year) in the Toka catchment area is the product of the above calculated factors (rain erosivity, erodibility, slope factor, cover management factor, support factor). *GRASS GIS version 5.0* [4] has been used to calculate the erosion in the Toka catchment area. The calculation was done in r.mapcalc function, which is a very powerful function in GRASS GIS for map algebra. Mapcalc > erosion = rfactor * lsfactor * kfactor * cfactor * pfactor [11].

The value ranges of erosion were estimated in the two studied cases: average intensity rain (A) and heavy intensity rain (B). A=160*LS*K*C*1
B=500*LS*K*C*1

The quantitative output of the predicted solid material loss was grouped in 5 classes (Table 2).

Table 2 Soil erosion potential categories

Erosion class	Numeric range t/ha/year	Soil erosion potential
0	0–1	Very low
1	1–10	Low
2	10–30	Moderate
3	30–80	High
4	> 80	Very high

The potential soil erosion map for case A and B was prepared based on the annual solid loss output data (Figure 4).

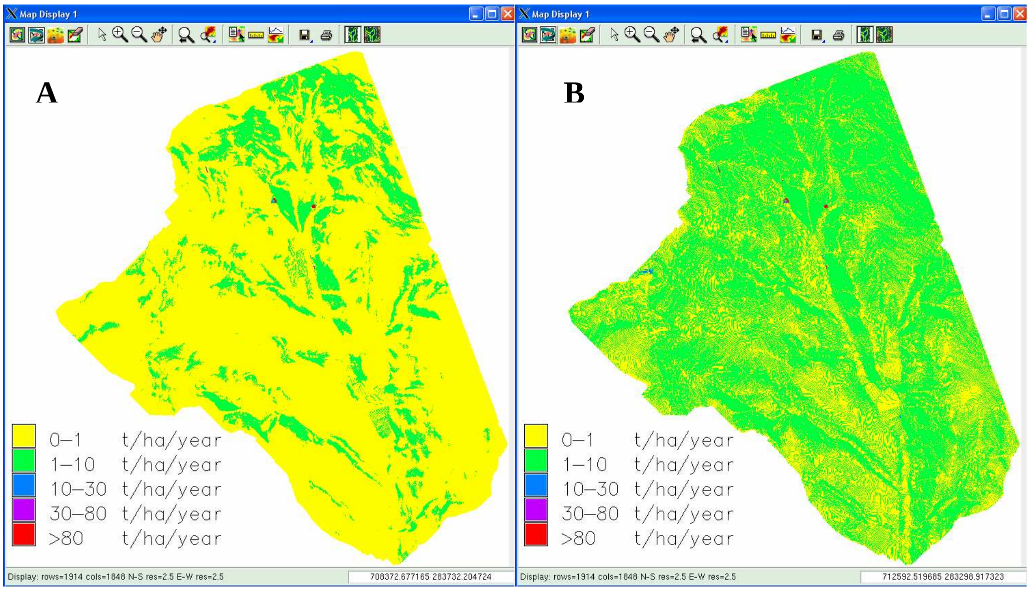

Figure 4 Potential Erosion classes in the Northern catchment of Toka creek (A and B cases)

Results and Discussion

GRASS GIS has been applied to calculate the potential erosion [11] in the Northern catchment of the Toka creek. The management practice factor "P" in this study is assumed to be 1.0, meaning that there is no erosion protection in the area. Two cases were discussed: in case „A" the erosivity of the average annual rain, in case „B" the erosivity of the high intensity annual rain. The erosion calculation parameters for the studied cases are summarised in Table 3 below.

Table 3 Erosion parameters in case A and B

Rain intensity	Annual average rain [mm/year]	24 hours rainfall with a recurrence of 2 years [cm/24 hours]	1 hours rainfall with recurrence of 2 years [cm/hour]	Soil erodibility K [–]
A (average)	756	7.4	0.18	0.12 and 0.23
B (high)	756	10.5	0.53	0.12 and 0.23

The average annual solid material loss and total erosion was calculated for the Northern catchment of Toka creek and for the identified mine waste dumps within the watershed. In the erosion calculations two different soil erodibility values were used: 0.12 for forests and 0.23 for mine waste dumps.

The results were classified in 5 groups. Table 4 shows the areas within the Toka watershed relevant to the GRASS GIS erosion classes and gives the % distribution of each area compared to the total Northern Toka watershed (1 062 ha).

Table 4 Areas of different erosion classes in the Northern Toka watershed in case A and B

Erosion class	**Ranges t/ha/year**	**Area (ha) case A**	**% Area case A**	**Area (ha) case B**	**%Area case B**
0 very low	0–	882.968750	83	379.405625	35
1 low	1–10	178.417500	16	681.669375	64
2 moderate	10–30	0.078125	0.007	0.311250	0.29
3 high	30–80	0.080000	0.0075	0.078125	0.0073
4 very high	>80	0.182500	0.017	0.262500	0.024
Total		1062	100	1062	100

In case of average intensity rain (A) 83% of the studied area belongs to the very low, 16% to the low erosion class and only 0.017% belongs to the very high erosion class. In case of high intensity rain (B) only 35% of the total area belongs to the very low erosion class and 64% to the low erosion class and 0.024% to the very high erosion class. The relatively small area in the very high erosion class is identical with the area of the mine waste dumps, resulting therefore multiple increase of the metal emission due to erosion. The soil erosion map was produced from the annual solid loss output data (Figure 4).

Total erosion was calculated with GRASS GIS for the total Northern Toka watershed and (Table 5) for the non-vegetated surface of the mine waste dumps, mostly exposed to erosion (Table 6). The results are summarised for case A and B in Table 5 and 6:

Table 5 Erosion in the Northern Toka watershed

	case A	case B
Total erosion (t/year)	337	1053
Cell number	1698763	1698763
Area (ha)	1062	1062
Minimum (t/ha/year)	0,006	0,02
Maximum (t/ha/year)	348	1088
Standard deviation	3.2	9.9
Average (t/ha/year)	0.3	1.0

Table 6 Erosion of the mine waste dump area

	case A	case B
Total erosion (t/year)	47	147
Cell number	773	773
Area (ha)	0.5	0.5
Minimum (t/ha/year)	0.9	2.8
Maximum (t/ha/year)	348	1088
Standard deviation	111	348
Average (t/ha/year)	97	304

According to GRASS GIS total erosion is calculated summarising the annual solid loss unit values per cell. The cell numbers were read by GRASS GIS. The area of a cell is 6.25 m^2 (2.5 m * 2.5 m). For this reason 6.25 / 10 000 correction factor was applied when calculating total erosion of the area.

The maximum, minimum and average potential solid material loss in the Northern Toka watershed and in the mine waste dumps area was calculated. The figures in table 5 and 6 are statistical estimates and refer to the highest, lowest and mathematical average values of the considered cells. The GRASS GIS shows under which conditions (K, LS) and where do the maximum and minimum soil loss values occur and enables reading of the near to average values.

The solid material loss per hectar unit value changes from cell to cell in the GRASS GIS. This is the reason why the estimated average values cannot be used. The total erosion (t/year) values were the basis of our further work.

Tables 7 and 8 provide a comparison between the potential erosion of the Northern Toka watershed and the erosion of the mine waste dumps area located within the watershed in case of average rain (A) and heavy rain (B). To ease the comparison the eroded material quantity in the waste dump area was given in % of the total erosion in the Northern Toka catchment both in case A and B. Furthermore, the tables show in % of the total Northern watershed the minimum, maximum and average solid loss values in the mine waste dump area.

Table 7 Erosion of the mine waste dumps compared to the total Northern Toka watershed (A)

A case: average rain	Total Northern watershed	Mine waste dumps	Ratio of mine waste dumps %
Total erosion t/year	337	47	14%
Cell numbers	169 8763	773	0.5%
Area ha	1 062	0.5	0.5%
Minimum t/ha/year	0.006	0.9	15 000%
Maximum t/ha/year	348	348	100%
Standard deviations	3.2	111	
Average t/ha/year	0.3	97	30 000%

Table 8 Erosion of the mine waste dumps compared to the total Northern Toka watershed (B)

B case: heavy rain	Total Northern watershed	Mine waste dumps	Ratio of mine waste dumps %
Total erosion t/year	1053	147	14%
Cell numbers	1698763	773	0.5%
Area ha	1062	0.5	0.5%
Minimum t/ha/year	0.02	2.8	14 000%
Maximum t/ha/year	1088	1088	100%
Standard deviations	9.9	348	
Average t/ha/year	1	304	30 400%

The above tables show that the mine waste dumps area is only 0.5% of the Northern cathment of the Toka creek, however they produce 14% of the total erosion. The minimum solid loss from the very low erosion category non-vegetated surface of the mine waste dumps is 150 times higher than the similar category solid loss in the total Northern watershed and 300 times higher in case of the moderate erosion category. The solid loss in case of the very high erosion category areas, represented by the mine waste dumps, is identical with the solid material loss of the total Northern Toka watershed. The standard deviation values show the variability of the values and the deviation from the average of the total number of cells.

Metal emission is an important parameter of Hazard Assessment. The solid phase related metal emission was assessed with the GRASS GIS erosion model. According to the typical metal concentration ranges, to the rain and soil conditions of the area, the predictable As, Pb, and Cd, Cu, Zn emission of the eroded solid material from the total Northern Toka watershed and mine waste dump area was modelled. The metal emission calculations operated with minimum and maximum concentration mine wastes (Table 9) and moderate forest soil concentrations from the watershed (Table 9).

Table 9 Toxic metal concentration of the mine wastes and forest soil in the Toka watershed

Mine waste and soil	**Average concentration mg/kg**				
	As	**Cd**	**Cu**	**Pb**	**Zn**
Minimum concentration mine waste	240	5	120	500	500
Maximum concentration mine waste	2000	20	200	10000	4000
Forest soil in the Toka watershed	60	1	80	200	200

Tables 10 and 11 below provide a summary of the erosion induced metal emission of the average forest soil and minimum and maximum concentration mine waste in case of average (A) and high intensity (B) rain. Table 10 provides a summary of case A and B on the metal emission from the Toka Northern watershed area forest soil less the mine waste dumps (1061.5 ha), of the metal emission only from the mine waste dumps (0.5 ha) and of the total metal emission from the total Northern watershed inclusive of the mine waste dumps(1062 ha), assuming minimum (Table 10) and maximum (Table 11) concentration waste and average forest soil, average rain (A) and heavy rain (B) cases.

Table 10 Erosion produced yearly metal emission in case of minimum concentration mine waste

Cases	**Erosion t/year**	**Metal concentration of the eroded material mg/kg**					**Erosion produced metal emission kg/year**				
		As	**Cd**	**Cu**	**Pb**	**Zn**	**As**	**Cd**	**Cu**	**Pb**	**Zn**
A watershed(forest) (1061.5)	296	60	1	80	200	200	18	0.3	24	59	59
A mine waste dump (0.5 ha)	47	240	5	120	500	500	11	0.2	6	24	24
A total watershed(1062 ha)	337						29	0.5	30	83	83
B watershed(forest) (1061.5)	906	60	1	80	200	200	54	0.9	72	181	181
B mine waste dump (0.5 ha)	147	240	5	120	500	500	35	0.7	18	74	74
B total watershed (1062 ha)	1053						89	1.6	90	225	225

According to the model metal emission from the 0.5 h mine waste dump area in case of minimum concentration mine waste (Table 10) and average intensity rain (A) produced yearly erosion results: As: 11 kg, Cd: 0.2 kg, Cu: 6 kg, Pb: 24 kg and Zn: 24 kg. The heavy rain produced yearly erosion (B) results three times the metal emission of the average rain.

In spite of the fact that the mine waste dump area is only 0.5%-of the total Northern watershed and produces only 14% of the total erosion of the watershed, the erosion induced metal emission of minimum concentration mine waste dump areas in case of average and heavy intensity rain represent considerable weight compared to the metal emission of the average forest soil areas in the Toka watershed: As: 63%, Cd: 70%, Cu: 25 %, Pb: 40 %, Zn: 40 %. Due to this, the metal emission needs attention even in case of minimum concentration mine waste.

Assuming maximum concentration mine waste (Table 11), the yearly emitted metal amount from the mine waste dump areas under average intensity rain (A) conditions is: As: 94 kg, Cd: 0.9 kg, Cu, 9 kg, Pb: 470 kg , Zn: 188 kg, and As: 294 kg, Cd: 3 kg, Cu: 29 kg, Pb: 1 470 kg, Zn: 588 kg under heavy rain conditions (B).

Table 11 Erosion produced yearly metal emission in case of maximum concentration mine waste

Cases	Erosion t/year	Metal concentration of the eroded material mg/kg					Erosion produced metal emission kg/year				
		As	Cd	Cu	Pb	Zn	As	Cd	Cu	Pb	Zn
A watershed(forest) (1061.5)	296	60	1	80	200	200	17.8	0.29	24	59.2	5.2
A mine waste dump (0.5 ha)	47	2000	20	200	10000	4000	94	0.9	9	470	188
A total watershed(1062 ha)	337						111.8	1.19	33	529	247
B watershed(forest) (1061.5)	906	60	1	80	200	200	54.4	0.9	72.4	181	181
B mine waste dump (0.5 ha)	147	2000	20	200	10000	4000	294	3	29	1470	588
B total watershed (1062 ha)	1053						348	3.9	101	1651	769

The mine waste dump area (0.5 ha) supplies 14% of the eroded quantity of the total area (1 062 ha), however in case of maximum concentration mine waste the 14% results several times more metal emission. Maximum concentration mine waste dump areas emit by yearly erosion 4.5 times more As, 2.6 times more Cd, 7.0 times more Pb and 2.7 times more Zn, than the Toka Northern watershed forest soil (less mine waste dumps). The heavy rain produced yearly erosion (B) results three times the metal emission of the average rain.

To reduce metal emission from the diffuse and residual pollution after removal of point sources in the abandoned mining areas, combined chemical and phytoremediation technology was planned. Chemical stabilisation immobilises toxic metals in the soil and stimulates plant growth. Phytostabilisation hinders pollution transport both through water and solid phase, reducing infiltration, seepage and erosion. According to the results of our field experiments the joint effect of chemical and phytostabilisation (CCP) is able to reduce Cd, Pb and Zn emission transported by surface runoff [5], [5a] [6], in order to comply with the environmental criteria for sensitive water usage [5], [5a] [6], [10]. The As emission can be reduced to the target by controlling its transport in the dissolved and solid phase. [5], [6], [10].

The emission mitigation effect of complex chemical and phytostabilisation (CCP) was predicted with the GRASS GIS erosion model.

GRASS GIS model aided prediction of the erosion mitigation effect of CCP

The erosion mitigation effect of CCP in the 0.5 ha mine waste dump area was studied with the GRASS GIS model in case of minimum (Table 12) and maximum concentration mine waste (Table 13), assuming average (A) and heavy (B) rain events.

Table 12 Erosion and metal emission mitigation by CCP in case of mine waste of minimum metal concentration

Cases	Erosion t/year	Metal emission kg/year				
		As	Cd	Cu	Pb	Zn
Before phytostabilisation						
A waste dumps (0.5 ha)	47	11	0.2	6	24	24
B waste dumps (0.5 ha)	147	36	0.7	18	74	74
After phytostabilisation						
A waste dumps (0.5 ha)	0.139	0.033	0.0007	0.017	0.069	0.069
B waste dumps (0.5 ha)	0.426	0.102	0.002	0.051	0.213	0.213
Emission mitigation (%)						
A waste dumps (0.5 ha)	99.7	99.7	99.7	99.7	99.7	99.7
B waste dumps (0.5 ha)	99.7	99.7	99.7	99.7	99.7	99.7

According to the GRASS GIS erosion model 14% of the annual erosion in the studied Toka watershed (1 062 ha) originates from the mine waste dump areas (0.5ha) (Table 7 and 8). The remaining 1061.5 ha of the watershed includes mainly forests. The annual erosion of the watershed is 337 t/year, in case of average rain and 1 053 t/year in case of heavy rain. Out of these erosion values the relevant erosion of the mine waste dumps is 47 t/ha and 147 t/ha, respectively. Consequently, the erosion in the vegetated forest area (1061.5 ha) is 296 t/year and 906 t/year, respectively.

Table 13 Erosion and metal emission mitigation by CCP in case mine waste of maximum metal concentration

Cases	Erosion t/year	Metal emission kg/year				
		As	Cd	Cu	Pb	Zn
Before phytostabilisation						
A waste dumps (0.5 ha)	47	94	0.9	9	470	188
B waste dumps (0.5 ha)	147	294	3	29	1470	588
After phytostabilisation						
A waste dumps (0.5 ha)	0.139	0.278	0.0028	0.028	1.39	0.56
B waste dumps (0.5 ha)	0.426	0.852	0.0085	0.085	4.26	1.70
Emission mitigation (%)						
A waste dumps (0.5 ha)	99.7	99.7	99.7	99.7	99.7	99.7
B waste dumps (0.5 ha)	99.7	99.7	99.7	99.7	99.7	99.7

According to Table 12 and 13 if we assume that after CCP the annual erosion rate in the mine waste dump area (0.5 ha) would be similar to the erosion of the vegetated forest area, the average and heavy rain induced erosion of the mine waste dump areas after CCP would decrease from 47 t/year to **0.139 t/year** and the heavy rain induced erosion from 147 t/year to **0.426 t/year.** This is 99.7% decrease in the yearly quantity of the eroded material. The metal emission from the minimum and mine waste dumps of maximum metal concentration area both in case of average and heavy rain is 99.7%.compared to the status before CCP.

The arsenic is the most problematic toxic metal emission associated with transport by erosion in the mine waste dump area. CCP even in case of the most polluted mine waste area (Table 13) would reduce As emission from 94 kg/year to **0.278 kg/year** in case of average rain induced erosion and from 294 kg/year to **0.852 kg/year** in case of heavy rain induced erosion.

The metal emission mitigation effect of CCP was estimated with the aid of the GIS GRASS model. In case of maximum concentration mine waste CCP of the mine waste dump area would mitigate average intensity rain induced erosion such as to decrease Cd emission from 0.9 kg/year to 0.0028 kg/year, Cu emission from 9 kg/year to 0.028 kg/year, Pb emission from 470 kg/year to 1.39 kg/year, Zn emission from 188 kg/year to 0.56 kg/year. Heavy intensity rain induced erosion mitigation by CCP would result the following metal emission decrease: Cd emission from 3 kg/year to 0.0085 kg/year, Cu emission from 29 kg/year to 0.085 kg/year, Pb emission from 1470 kg/year to 4.26 kg/year, Zn emission from 588 kg/year to 1.70 kg/year. The 99.7% reduction of the solid phase related metal emission due to erosion together with the mitigated metal emission in the dissolved phase [5], [5a] [6] is able to satisfy the requirements of the Environmental Quality Criteria even in case of As.

Conclusions

According to the GRASS GIS model the mine waste dump area in the Northern catchment of Toka creek is the land use category exposed to the highest erosion. Although the mine waste dump area is only 0.5% of the area of the Northern Toka catchment it produces 14% of the erosion of the studied catchment. In case of a highly polluted mine waste material the 14% results many times higher metal emission. The solid phase related metal emission was estimated by the GRASSS GIS erosion model. Taking into account the minimum, maximum pollution levels, the soil quality in the area, the average annual rain and soil conditions, the yearly erosion, the metal (As, Pb and Cd, Cu, Zn) emission of the eroded material was modelled. Given that the As and Pb transport is connected to the solid phase, the As and Pb emission due to average and heavy rain induced erosion of minimum and maximum concentration mine waste is higher than the Cd and Zn emission dominating in the water phase.

With the aid of the GRASS GIS erosion model the erosion mitigation effect of CCP planned to be employed on the 0.5 ha surface area of the mine waste dumps was estimated both for the average and heavy intensity rain induced erosion cases, assuming minimum and maximum concentration waste material.

According to the results of the CCP field experiments the joint effect of chemical and phytostabilisation is able to reduce Cd, Pn and Zn emission of the mine waste, such as to comply with the environmental criteria set for sensitive water use. The 99.7% reduction of the solid phase related metal emission due to erosion together with the mitigated metal emission in the dissolved phase [5a], [5] [6] is able to satisfy the requirements of the Environmental Quality Criteria even in case of As.

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