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ASSESSMENT OF SOIL EROSION IN THE CATCHMENT OF TWO COMBINED CLOSED DEPRESSIONS IN THE NAŁĘCZÓW PLATEAU (LUBLIN UPLAND)

Anna Rafalska-Przysucha, Jerzy Rejman

Institute of Agrophysics, Polish Academy of Sciences
ul. Doświadczalna 4, 20-290 Lublin
e-mail: a.rafalska@ipan.lublin.pl

A b s t r a c t. The aim of the study was to evaluate the intensity of soil erosion within the catchment of two closed depressions in the Nałęczów Plateau (Lublin Upland). The amount of erosion was assessed from the depth of accumulated soil material, and the calculated amount was related to the time of agricultural land use. The studies were carried out in the catchment of the area of 0.54 ha. Within the catchment, 75 intact soil cores were taken and analysed to determine the depth of soil horizons and accumulated soil material. Depositional soils were represented by 25 soil cores. The average thickness of the accumulated material was 0.75 m with a maximum of 1.78 m. The results showed that the catchment of two combined closed depressions evolved to the form of a small valley (trough) after 185 years of agricultural use. The volume of soil material accumulated in the catchment, calculated from the thickness of the depositional material in soil profiles collected in a regular grid, was 1797.4 m^3, and the volume calculated from the profiles located in transects that crossed the catchment axis was higher by 2%. The average rate of erosion in the catchment of the two combined depressions was 24.3 Mg ha^{-1} yr^{-1}.

K e y w o r d s : erosion, closed depression, loess, soil profile, Haplic Luvisol

INTRODUCTION

Closed depressions are defined as landforms where hill slopes encircle a common sediment depository, and the sediment eroded from the surrounding hill slopes is trapped inside the system (Norton 1986). In areas under agricultural use, closed depressions gradually disappear as a result of translocation of soil from the slopes to the bottom of the depression due to water and tillage erosion, and are often poorly marked in the topography. The main indicator of its presence are the zones of water stagnation during snow melting. The stagnation of water often results in destruction of plants due to limited amount of oxygen in soil.

Closed depressions are one of the most characteristic geomorphic forms of loess areas (Maruszczak 1955). The density of closed depressions is high and varies between 1 and 16 per km^2 (Vanwalleghem *et al.* 2007, Kołodyńska-Gawrysiak and Chabudziński 2012). Large amounts of depressions and processes of erosion and accumulation in closed depressions contribute to the enormous diversity of soils in loess areas, which was found by Turski *et al.* (1992) and Rejman (2013). Yet, the rate of filling of closed depressions by the depositional material is relatively poorly recognised. To assess the rate of erosion or sedimentation within the closed depression, the volume of accumulated material, the area of catchment and period of agricultural land use should be determined. The volume of accumulated soil material is calculated from the analysis of soil cores located in a regular grid (Norton 1986, Frielinghaus and Vahrson 1998) or transects along and across the axis of the catchment (Gillijns *et al.* 2005, Vanwalleghem *et al.* 2007).

The main aim of the study was to determine the intensity of soil erosion within the catchment of two closed depressions in the loess part of the Nałęczów Plateau (Lublin Upland, Poland). The additional aim was a comparison of the volume of accumulated soil calculated from the analysis of thickness of the accumulated soil material in profiles located in a regular grid and transects along and across of the catchment axis.

MATERIAL AND METHOD

The studies were carried out in Bogucin (51º19'56"N latitude and 22°23'18"E longitude), in the Nałęczów Plateau (Lublin Upland). Loess deposits are about 10-30 m thick and underlie glacigenic deposits of Odranian (Saalian) glaciations that are located on complexes of tertiary and cretaceous rocks (Harasimiuk and Henkiel, 1976). The study site was the catchment of two closed depressions with a total area of 0.54 ha, and altitudes that ranged from 223.5 m to 225.7 m a.s.l. (Fig. 1). The catchment is located within two arable fields, and the agricultural land use of the site started in 1820 (Rejman 2006).

Brown-grey soils (Haplic Luvisols) developed from loess are typical soils for the study area. Soil sampling was performed in a regular grid of 10x10 m in the autumn of 2005. In total, 75 intact soil cores were collected and the soils were classified according to Turski *et al.* (1987). The samples were taken to the depth of calcareous loess in non-eroded and eroded soils, and to the lower border of the BC horizon in depositional soils. The thickness of soil horizons was determined on the basis of colour and consistency of the soil. The depth of calcareous loess was assessed by the soil reaction with 10% hydrochloric acid.

Fig. 1. The studied closed depressions with stagnated water during snowmelt

A topographic map of the study area was developed from geodetic measurements with a tachymeter Nikon DTM 330. The map was produced in Surfer v. 10 (Golden Software Inc. 2011). To produce the map, the kriging method with a linear model was applied. The catchment boundary was determined on the basis of topographic map and distribution of the soils (Fig. 2).

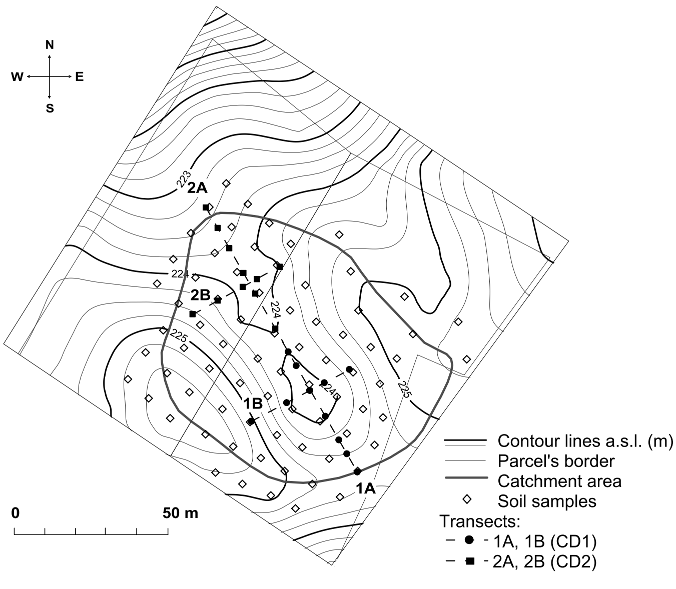

Fig. 2. Study area with points of collection of soil cores, catchment boundary and transects in the first (CD1) and second (CD2) closed depression

Calculation of the volume of material deposited in the catchment based on the analysis of thickness of depositional material in the profiles located in a regular grid

The development of a topography map without depositional material was the first step in the calculations of the volume of depositional material. The map was produced in Surfer with the use of kriging method with a linear model. The elevation points for the map were obtained from the difference between the altitude of measured points and the thickness of depositional material (Ap-C1). Then, the volumes of soil material between the 0 m a.s.l. contour line and the contour lines for the current topography and topography without the accumulated material were calculated using the Grid+Volume procedure of Surfer ver.10. The volume of accumulated material was calculated from the difference of the volume of material in current topography and topography without accumulated material.

Calculation of the volume of material deposited in the catchment based on the analysis of thickness of depositional material in the profiles located in transects

The transects were located along and across the axis of depressions CD1 and CD2 (Fig. 2). The length of transects was 50 and 36 m in CD1. The longer transect (1A) consisted of seven and shorter (1B) of five cores. The length of the transects was 49 and 32 m in CD2, and the longer transect (2A) consisted of six and the shorter (2B) of five cores. In total, 17 cores with depositional and 6 with the other soils were used to calculate the volume of accumulated soil material.

The volume of material deposited in the catchment was calculated from the product of the average thickness of the deposited soil material that was located along two transects and the surface area with accumulated soil material:

$$V = D_{śr} \cdot P \tag{1}$$

where: V is the volume of the accumulated soil material (m^3), $D_{śr}$ - the average depth of the accumulated material (m), P - the surface area with accumulated material (m^2). The surface area was calculated from the formula for the average ellipse area:

$$P = \pi \frac{1}{4}(ab + bc + cd + da) \tag{2}$$

where: a and c are the radii of ellipses along the depressions axis, b and d are the radii of ellipses across the depressions axis (Fig. 3). The volume of depositional material was calculated separately for the two depressions, and then summed.

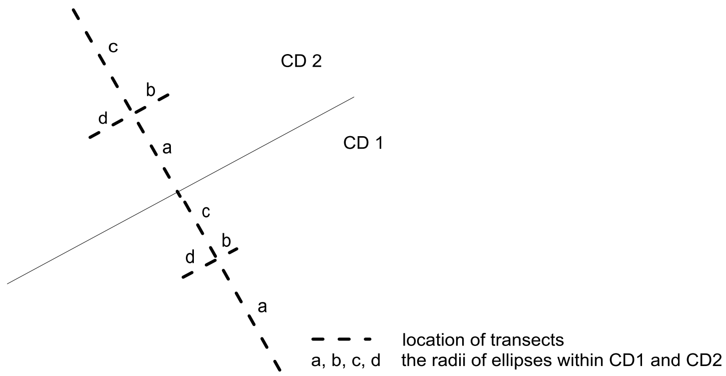

Fig. 3. Location of transects and ellipses radii in the depressions

Calculation of the mass of accumulated soil material

The mass of accumulated soil within the catchment was calculated based on the volume of depositional material, using the formula:

$$m = \rho \cdot V \tag{3}$$

where: m is the mass of soil (Mg), ρ – the density of soil (Mg m^{-3}), and V - the volume of depositional material (m^3). The soil density of 1.35 Mg m^{-3} was used in the calculation of mass of accumulated soil material.

RESULTS

Soils in the closed depressions

Depositional soils were the most frequent and amounted to 33% of the total number of cores, and non-eroded and severely eroded soils were the least with 11 and 9%, respectively (Fig. 4). Depositional soils were located in the bottom of the depressions, non-eroded and slightly eroded soils at the foot of the slopes, and moderately and severely eroded soils at the border of the catchment. The distribution of depth of soil horizons along transect 1B in the closed depression CD1 is shown in Figure 5.

The average thickness of solum (Ap-BC) of non-eroded soils was 1.52 m, with standard deviation (SD) of 0.18 m. The thickness of solum of eroded soils was smaller and ranged from 0.53 to 1.2 m for severely eroded soils (with SD = 0.14 m) and for slightly eroded soils (0.21 m), respectively. The average thickness of moderately eroded soils was 0.73 m (0.14 m). Depositional soils were the deepest, and the average thickness of solum was 2.58 m (0.77 m). The depth of accumulated soil material (Ap-C1) in depositional soils ranged from 0.25 to 1.78 m, with a mean of 0.75 m and median of 0.64 m (SD = 0.48 m). The range from 0.26 to 0.75 m was the most frequent, and represented 48% of the total number of cores with accumulated soil material (Fig. 6).

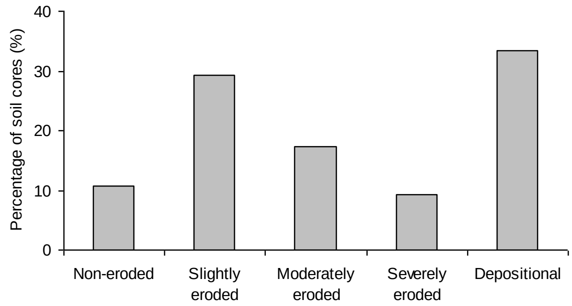

Fig. 4. Percentage of soils in the catchment

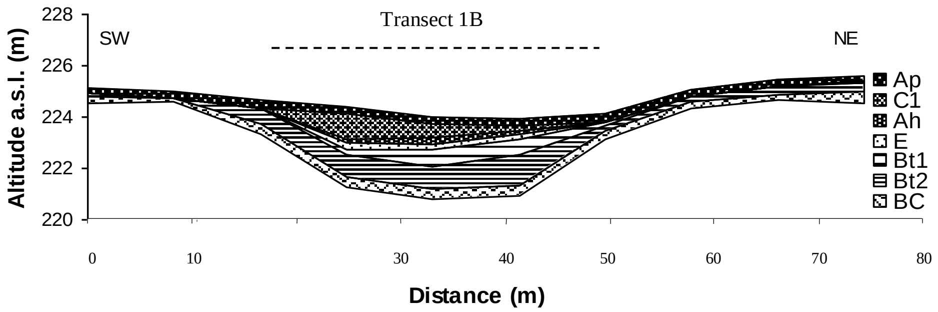

Fig. 5. Distribution of soil horizons in the cross-section of CD1 (dashed line - transect 1B)

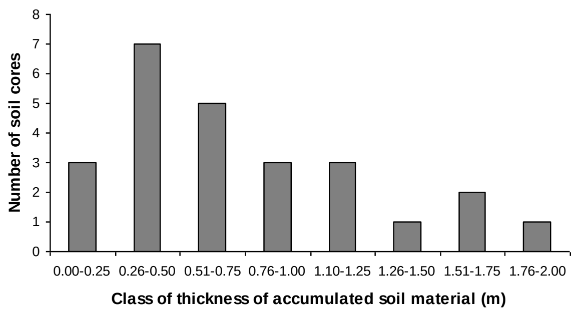

Fig. 6. Distribution of classes of thickness of accumulated soil material

Volume and mass of accumulated soil material in the catchment

Present-day topography and topography after the removal of depositional material of the studied area is presented in Figure 7. The maps well depict the transformation of relief after 185 years of agricultural land use. Removal of depositional soil material proved that the study area consisted of two separate closed depressions in the past. At present, the depressions are combined in the form of a small valley (trough). The total volume of material deposited in the catchment, calculated on the basis of cores in regular grid and the procedure of Grid+Volume of the Surfer program, was 1797.42 m^3. Taking into account the assumed value of soil density of 1.35 Mg m^{-3}, the total mass of the depositional material was 2426.52 Mg. The maximum value of bulk density of brown-grey soil was found in the Bt horizon i.e., at the depth from 0.4 to 1.1 m, and reached 1.65 Mg m^{-3} (Klimowicz *et al*. 2006). Taking into account the maximum value of bulk density in calculations of the total mass of the depositional material and the average erosion rate, the values could increase maximally up to 1.2 times in comparison to the previously calculated rates.

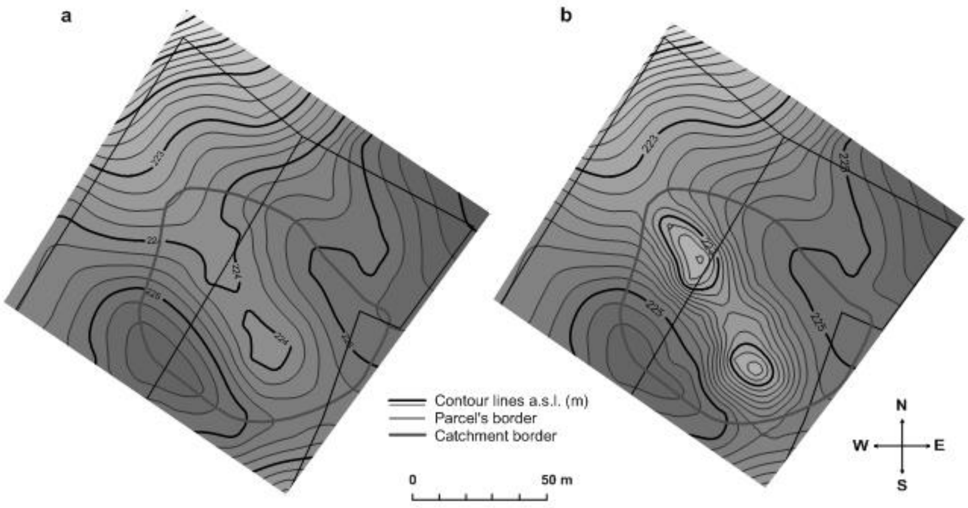

Fig. 7. Topography of the study area with (a) and without (b) accumulated soil material

The value recalculated to the present-day catchment area amounted to 4493.6 Mg ha^{-1}, and the average erosion rate during the period of agricultural land use was 24.3 Mg ha^{-1} yr^{-1}.

Next, the volume of accumulated soil material was calculated for soil cores in transects located along and across the catchment axis. The areas of ellipses were similar in both closed depressions, and the thickness of depositional material in CD1 was smaller by 0.2 m in comparison to CD2 (Tab. 1). The difference resulted in larger amount of deposited material in the latter. Total volume of depositional material in both depressions was 1833.71 m^3, and the value was larger by 36.29 m^3 (i.e. by 2%) in comparison to the volume that was calculated with the use of the Grid+Volume option.

Table 1. Average volume of depositional material within CD1 and CD2, and total volume of depositional material in the catchments of the two closed depressions

Closed depression	Average thickness of depositional material (m)	Radius of ellipse (m)				Mean area of ellipse (m^2)	Average volume of depositional material (m^3)
		a	b	c	d		
CD1	0.60	31	15	19	21	1413.0	851.1
CD2	0.80	21	11	28	21	1230.9	982.6

Summarising, the volume of accumulated soil material calculated from soils profiles located in a regular grid of 10 x 10 m and transects was similar. Smaller amount of soil cores that were used to calculate the volume of accumulated soil material is the advantage of the latter. However, this method requires a proper establishment of transects that should be oriented along and across the catchment axis. For both methods, a larger number of measurement points may be necessary in the case of problems in delimitation of the catchment border.

DISCUSSION

The area of closed depressions in the loess belt of the Nałęczów Plateau ranges from 56 to 40 000 m^2. A majority of the depressions are small, with area less than 1500 m^2 and diameter below 80 m (Kołodyńska-Gawrysiak and Chabudziński 2012). The studied depressions in Bogucin with the combined area of catchment of 2700 m^2 and diameter of 50 m well represent the average size of the closed depressions in the region.

The study showed that the processes of water and tillage erosion have induced a significant transformation of the topography in the area that has remained under cultivation for 185 years. The study area, that is now in the form of a small valley (trough), consisted of two separate closed depressions before the start of the agricultural land use. The transformation of topography has led to a large diversity of soils in the catchment. The eroded soils are the most frequent and represent 56%, and depositional and non-eroded soils 33% and 11% of the total cores, respectively. The percentage of soils in the catchment of the two closed depressions slightly differs in comparison to the soil distribution in the catchment of a dry valley, a part of which is the study area (Rejman 2013). The studied area consists of about 4% more slightly eroded soils, and 6 and 3% less of non-eroded and severely eroded soils, respectively, in comparison to the whole catchment area. The percentage of depositional soils is similar. Compared to the area studied by Turski *et al.* (1992), the area of the catchment of the two closed depressions contains more slightly eroded soils (by 11%) and less severely eroded soils (by 12%).

The calculated soil erosion rate in the studied closed depression has been compiled with the data presented by other authors (Tab. 2). A similar rate of erosion at comparable time of agricultural use was observed in loess areas of North America by Norton (1986). In contrast to this, smaller rates of erosion were observed in the loess belt of Belgium (Gillijns *et al*. 2005), and in the moraine terrain of east Germany (Frielinghaus and Vahrson 1998).

Table 2. Soil erosion rate in closed depressions

Source	Erosion	Time of agricultural land use	Erosion rate	Soil texture
	(Mg ha^{-1})	(years)	(Mg ha^{-1} year^{-1})	
Present study	4494	185	24.29	silt-loam
Bollinne (1982)*	2601	145	17.94	silt-loam
Bollinne (1983)*	2262	145	15.60	silt-loam
Bollinne (1984)*	1856	170	10.92	silt-loam
Frielinghaus and Vahrson (1998)	9000	600	15.00	silt-loamy sands
Gillijns *et al*. (2005)	375	49	7.65	silt-loam
Norton (1986)	3900	145	26.90	silt-loam

*– after Gillijns *et al*. 2005.

CONCLUSIONS

1. Processes of erosion and accumulation resulted in transformation of two closed depression in the form of a small valley (trough) after 185 years of agricultural use.

2. Transformation of topography induced a large diversity of soils in the catchment. Depositional soils are located in the bottom of depression, non-eroded and slightly eroded soils at the foot of the slopes, and moderately eroded and severely eroded soils at the border of the catchment.

3. The volume of accumulated material calculated from the analysis of soil profiles located in transects and regular grid was similar, and the difference in volume between both methods was 2%.

4. The average annual rate of erosion in the catchment of the two combined closed depressions was 24.3 Mg ha^{-1} yr^{-1}.

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OCENA WIELKOŚCI EROZJI W ZLEWNI DWÓCH POŁĄCZONYCH ZAGŁĘBIEŃ BEZODPŁYWOWYCH NA PŁASKOWYŻU NAŁĘCZOWSKIM (WYŻYNA LUBELSKA)

Anna Rafalska-Przysucha, Jerzy Rejman

Institute of Agrophysics, Polish Academy of Sciences
ul. Doświadczalna 4, 20-290 Lublin
e-mail: a.rafalska@ipan.lublin.pl

Streszczenie. Celem pracy było określenie natężenia erozji gleby w obrębie zlewni dwóch zagłębień bezodpływowych na Płaskowyżu Nałęczowskim (Wyżyna Lubelska). Wielkość erozji została określona na podstawie miąższości zgromadzonego materiału glebowego. W zlewni o łącznej powierzchni 0,54 ha pobrano i poddano analizie 75 nienaruszonych rdzeni glebowych, w celu określenia miąższości poziomów glebowych oraz zakumulowanego materiału. Gleby deluwialne były reprezentowane przez 25 rdzeni. Średnia miąższość materiału zdeponowanego w zlewni wyniosła 0,75 m, a maksymalna 1,78 m. W ciągu 185 lat użytkowania rolniczego zlewnia zagłębień bezodpływowych uległa przekształceniu w formę niecki. Objętość materiału zgromadzonego w zlewni, obliczona z uwzględnieniem miąższości materiału depozycyjnego w profilach pobieranych w regularnej siatce, wyniosła 1797,4 m^3, a obliczona na podstawie profili zlokalizowanych w transektach, poprowadzonych wzdłuż i w poprzek osi zlewni była większa o 2%. Średnie roczne tempo erozji w zlewni połączonych zagłębień wyniosło 24,3 Mg·ha^{-1}·rok^{-1}.

Słowa kluczowe: erozja, zagłębienia bezodpływowe, less, profile glebowe, Haplic Luvisol