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Gully- or sheet erosion? A case study at catchment scale

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Abstract

Soils have become an increasingly important natural resource especially in an agricultural land such as Hungary. In addition to this sedimentation and eutrophycation pose a high risk for the landscape. To protect soil fertility and to maintain the good quality of freshwater resources it is necessary to clarify the connection between sheet and gully erosion. The aim of this paper is to present an analysis on erosion and sedimentation in a hilly watershed, i.e. in the Tetves catchment, Hungary. At the outlet of the basin a sediment reservoir can be found which has been filled up completely. The authors made an attempt to determine the origin of the sediment by investigating it in the reservoir. More topsoil underlines the role of sheet erosion in the catchment, while more subsoil in the reservoir means considerable gully erosion activity. Six sampling sites were appointed along the reservoir. At each point samples were taken as a collection of seven borings. Each profile was divided into horizons and altogether 32 samples were investigated. Humus content and Caesium-137 activity have been used as tracers of the topsoil. Gully erosion activity has been investigated in the whole catchment during three years (1968, 1984, and 2004) using maps, air photos and field survey.

Approximately half of the deposited sediments came from the subsoil layer. This fact proves the key role of gully erosion in the catchment. In addition the results show that the activity of gully erosion has a yearly fluctuation on one hand and a 5–10 years periodicity on the other. In general early springtime caused low volume topsoil to have been deposited in the reservoir and during the periods of thunderstorms (late summer) a high volume of subsoil was eroded and delivered beyond the limits of the basin. This periodicity can be seen in the stripped profile of the reservoir. According to both gully development and sedimentation, the most active period of subsoil sediment transportation occurred in the catchment between 1984 and 1995. Based on the investigations it can be estimated that roughly 10% of the soil eroded by gullies leaves the catchment while the rest is sedimented inside.

Keywords: Gully erosion, sheet erosion, sediment delivery, sediment reservoir, Caesium-137.

Introduction

Sediment deposition is part of the soil erosion process, although most of the investigations focus on soil loss. Sedimentation can be as dangerous as soil erosion from the point of view of agronomy and ecology. Investigating soil erosion on catchment scale it is very

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important to know the quantity of the eroded soil and its part that sedimented nearby. In general the largest portion of soil loss is deposited at the bottom of the slopes and only a few percent leaves the catchment. According to Fitzpatrick, E.A. (1986) soil loss delivered by sheet erosion can take small distances, while the sediment delivered by gully erosion often reaches the streams. In many cases gullies are not the sources of soil loss but as channels they can transport the sediment out of the catchment (Wischmeier, W.H. 1977). The ratio between gully and sheet erosion in a catchment can vary within wide ranges. The USLE (Wischmeier, W. H.–Smith, D.D., 1978) absolutely neglects linear erosion. According to De Vente, J.–Poesen, J. (2005) sediment sinks are of less importance in basins dominated by bank erosion. In other words gullies can increase the volume of sediment yield remarkably (Kertész, Á. 1984, 2004a,b). During heavy rainstorms the majority of the sediment leaving the catchment originates from linear erosion features, but the ratio can vary with time (Chaplot, V. *et al*., 2005). Generally speaking climatic conditions can determine the ratio between gully and sheet erosion Kertész, Á. 2006). Moreover considerable transformation in land use can cause changes in gully development as well (Gábris, Gy. *et al*. 2003).

The aim of this paper is to identify the 30 years sediment yield at the outlet of the catchment, to determine the volume of soil erosion in the basin and to distinguish between sediment from the surface (the uppermost 20 cm) and sediments from lower horizons. Temporal regime of erosion processes can be fixed with continuous investigations of both the development of gullies in the basin and the filling up of the reservoir. .

Materials and methods

The catchment area of the Tetves stream is about 120 km^2 and it belongs to the southern subcatchment of Lake Balaton, Hungary. Several soil erosion (Kertész, Á. *et al*., 2001, 2003; Jakab, G. *et al*., 2005, 2006) and landscape (Tóth, A.–Szalai, Z. 2007) studies have been made in the Tetves valley. The detailed description of the study site can be found elsewhere (Madarász, B. *et al*. 2003; Jakab, G. 2008a), in this paragraph only the related information is shown. To retain the eroded sediment a reservoir was constructed in 1970 with an area of 13 ha and capacity of 95,300 m^3. Although by 2000 the reservoir was completely filled up the stream is still flowing through. Beside the reservoir some fishponds can be found, which gain water also from the stream just above the reservoir. The fill of the ponds is possible only at high or mean water levels of the stream. In general the early springtime is the period of filling the ponds, because this is the time of the yearly flood. The sediment reservoir as well as the fishpond contains the deposited soil loss of the catchment.

Eroding and delivering of the subsurface parts of the profile are related to linear (gully) erosion, while the surface can be destroyed due to both linear and sheet erosion (Fitzpatrick, E.A. 1986). To reach the primary aim of the research an adequate method was needed that helps to make a difference between sediments of surface (topsoil) and subsurface (subsoil) origin. The first possibility is to distinguish according to the organic matter content.

This method can give additional information from the sedimented profile but because of the undefined borders between the groups it is not suitable for calculation. Another way is to use the particle size distribution of the sediments to find out the origin of the horizons. This method is based on the relatively homogeneous particle size distribution of the parent material (sandy loess) of the catchment. The expected results of this method are also only informative. The third method uses the Caesium-137 isotope as a tracer of the surface soil. Panin, A.V. *et al*. (2001) have used this method to investigate the soil loss related to linear and sheet erosion.

The method based on the measurement of Cs-137 isotope gives rapid results and well demonstrates the dimension and spatial distribution of the erosion and sedimentation processes (Bouhlassa S. *et al*., 1995), although it is less accurate than the conventional methods (Wicherek, S.P.–Bernard, C. 1995). This isotope is artificial and its presence in the environment is the result of nuclear weapon tests and accidents. The direct source of soil contamination is fallout. As the Cs-137 isotope reaches the surface it makes very strong complexes with clay minerals and with organic matter (Mabit, L.–Bernard, C. 1998). Since Cs-137 is an alkali metal cation, its behaviour is quite similar as phosphorus, although phosphorus has remarkably shorter radius (Killham, K. 2001).

That is why this isotope cannot be leached as a solved material. The contamination under average Hungarian conditions and in undisturbed soil profiles does not exceed the 25–30 cm depth (Szerbin, P. *et al*., 1999). The migration along the profile is possible only with the help of the clay minerals (Chappell, A. *et al*., 1998). In an undisturbed profile the total activity of the isotope decreases exponentially downwards from the surface (Porto, P. *et al*. 2001). If one does not find any activity concentration in the top of the profile it means that this profile is eroded. The presence of Cs-137 activity in deeper horizons means deposition of topsoil on the top of the original profile (Govers, G. *et al*. 1996; Lu, X.X.–Higgitt, D.L. 2000, 2001). Sampling should be done by layers of the profile and requires particular attention (Connor, D.M. *et al*., 1997).

The volume of the fallout was determined by using the reference profiles of Szerbin, P. *et al*. (1999) and Csepinszky, B. (2003). Along the axis of the reservoir six sampling points were established representing the whole deposited mass. At each point samples were taken as a collection of 7 borings. Each profile was divided into horizons and altogether 32 samples were investigated (Jakab, G. 2008c). In addition to this the fishpond was also sampled *(Photo 1).*

Gully erosion activity has been investigated in the whole catchment during three years (1968, 1984, and 2004) using maps, air photos and field survey (Jakab, G. *et al*. 2006).

Photo 1. Sampling points in the reservoir

Results

During the field survey in 2004 altogether 140 gullies were identified and mapped. Within this group of gullies only 85 were present in 1968 and 115 existed in 1984. Changes in total length of these gullies in time can be seen in *Table 1*. Before 1984 the increase in gully length was relatively slow while after 1984 the average gully increased with almost double velocity *(Fig. 2)*. During the research period (34 years) the total length of the gullies increased almost by 60%. Before 1984 the growth of the shortest (<50 m) gullies was typical, while after 1984 gullies longer than 450 m were the most important components of length increase. Probably the most important reason for the difference is the concentration of arable plots in the 1980s. Later another very important cause could be the failure of the abandoned ditches due to the field reprivatisation.

Table 1. Changes in gully length in time

Years	**1970**	1984*	2004
Total gully length (km)	29.9	36.7	47.1
Cummulative length (%)	100	123	158
Average increase (m $year^{-1}$)	–	173	519

* Air photos of 1984 do not cover the whole catchment area, there is a lack of data on 15 gullies. For these gullies data of the year 2004 were applied.

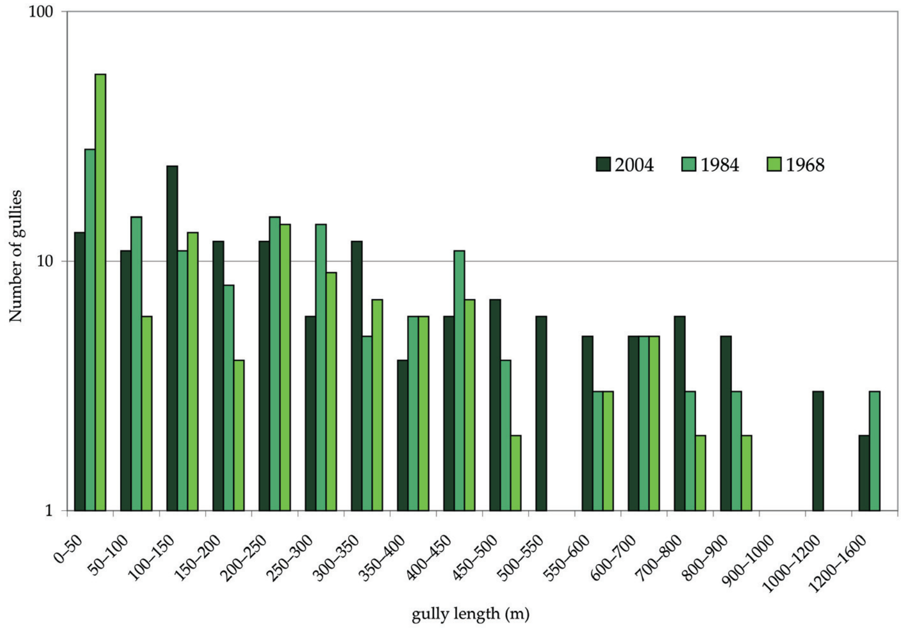

Fig. 2. Gully distribution according to their length in 1968, 1984, and 2004.
Note: vertical scale is logarithmic

Both processes have had a remarkable effect on increase of uncontrolled, concentrated surface runoff. Detailed results on this part of the study can be found in Jakab, G. *et al*. (2005) and Jakab, G. (2008b).

During the lifetime of the reservoir (1970–2000) the volume of the filling-up was 95,300 m^3. The filtering effect was more effective because of the high biomass production. In case of this wetland the annual production is about 2 kg m^{-2} (Begon, M. *et al*., 1996), with a bulk density of 1.0 g cm^{-1}. Such kind of riparian ecosystems highly affects the physical and chemical properties of the sediment (Szalai, Z. 2007; Szalai, Z.–Németh, T. 2008). This means 7,800 m^3 organic matter sedimentation during 30 years. The other 87,500 m^3 were filled up with sediments delivered from the catchment. The average bulk density of the undisturbed sediments in the reservoir is 1.3 g cm^{-1}. This means 113,750 t net soil loss during 30 years. From the point of view of areas of potential soil erosion in the catchment, the specific annual erosion rate is 0.8 t ha^{-1}. This value is based on a very rough estimation, but it may demonstrate the tendency and order of magnitude. It is very important to note that this sediment volume left the catchment. According to Kirkby, M.J.–Morgan, R.P.C (1980) the net soil loss is only a very small part of the total soil movement, there might be much higher erosion activity within the catchment.

In the sampled profiles of the reservoir layers of several cms could be found *(Photo 3)*. This kind of stripped design was typical of the whole reservoir. The sediment reaching the reservoir was classified according to time and not to the distance from the inlet. The different organic matter content and particle size distribution in these layers are not the result of the inside processes in the reservoir, but the result of the different sediment delivery processes in the catchment. Probably below a precipitation amount and/or intensity threshold value gullies only deliver sediments originating from sheet erosion. Above these threshold values gullies become sediment sources as well and transport a large amount of parent material into the sediment reservoir. These precipitations lead to the formation of subsoil layers (loess, without organic matter) in the reservoir profiles.

In the fishpond the thickness of the contaminated sediment layer is less than 20 cm, therefore this is the maximum value of the deposition from the catchment during the last 50 years. Because of the regular distribution *(Table 2)* there is no mixing or redistribution in the sediment layers. The pond is older than 100

Photo 3. Sediment layers in the sediment reservoir

Fig. 2. Gully distribution according to their length in 1968 1984, and 2004

Sampling point	Depth (cm)	Activity (Bq kg^{-1})	St. dev	Activity (Bq m^{-2})
Fish pond	0–5	159.4	2.9	10,361.48
	5–10	152.98	3.4	9,944.25
	10–15	82.49	5.6	5,362.36
	15–20	5.57	7.1	362.07
	20–60	0.2	–	–
	peat	0.2	–	–
	total	–	–	26,030.16
S1	0–20	25.0	0.5	–
	20–40	46.4	0.7	–
	40–60	9.2	0.3	–
	60–80	3.8	0.2	–
	80–100	2.8	0.2	–
	total	–	–	11,674
S2	0–20	23.5	0.5	–
	20–40	30.9	0.5	–
	40–60	34.4	0.5	–
	60–80	12.4	0.3	–
	80–100	7.3	0.3	–
	total	–	–	12,615
S3	0–10	26.6	0.6	–
	10–20	103.0	0.7	–
	20–30	24.7	0.4	–
	30–40	11.1	0.3	–
	40–50	7.7	0.2	–
	50–60	3.8	0.1	–
	total	–	–	15,773
S4	0–20	46.8	2	–
	20–40	14	0.5	–
	40–60	9.2	0.4	–
	total	–	–	16,492
S5	0–25	30.2	1.6	–
	25–50	3.3	0.2	–
	50–80	0.48	0.11	–
	80–110	0.07	0.06	–
	total	–	–	–
		–	–	10,756
S6	0–12	53.2	1.8	–
	12–24	1.35	0.1	–
	24–36	17.9	0.4	–
	tota	–	–	8,412

Note: vertical scale is logarithmic.

years, the contaminated layer is thinner than 20 cm, consequently the pond has a very limited sediment input from the catchment, although the activity of the contaminated layer is more than three times higher than the fallout. The investigated points in the reservoir have more or less the same order of activity as the fishpond has. The important difference in is the thickness of the contaminated layer. In the reservoir activity was detected also in the 110 cm deep layer.

It is assumed that the whole contaminated layer in the fishpond is part of the sediment from the catchment and not the result of the fish breeding. In this case, because of the similar area of the pond and the reservoir, the sediment volume is roughly 130 cm m^{-2} and therefore sediments of the pond and of the reservoir belong together *(Table 3).* The fishpond was constructed before the start of the fallout that is why the volume of the fallout (7,900 Bq kg^{-1}) is not originated from the catchment. Because of the same reason the volumes of the reservoir should be decreased as well.

Originally the contamination did not leach below 20 cm. According to our model calculations, if the whole sediment was of topsoil origin, than the total activity of the 130 cm is 6.5 times higher than that of the fallout (51,350 Bq m^{-2}). Smaller volumes mean that the sediment contains subsoil, without Cs-137 activity, as a consequence of gully erosion *(Table 3).*

Using the Cs-137 technique it can be concluded that minimum 50% of the sediment at the outlet of the catchment originates from layers below 20 cm of the soil profiles of the catchment. The lower parts of an in situ profile are eroded by gully erosion, which refers to an important role of linear erosion in this case.

According to former investigations (Jakab G. *et al*. 2005) 1,198,268 m^3 material has been moved in the Tetves catchment due to gully erosion. This amount was eroded since the formation of the investigated gullies. To suppose the direct link between the increase of gully length and soil loss it can be

Table 3. Measured and modelled activities at the sampling points

Sampling points	Fallout	Activity I.	Activity II.	Activity III.	Model	Topsoil
	Bq m^{-2} 20 cm^{-1}	Bq m^{-2} 110 cm^{-1}		Bq m^{-2} 130 cm^{-1}		%
S1	7,900	11,674	5,674	23,774	51,350	0.46
S2	7,900	12,615	6,615	24,715	51,350	0.48
S3	7,900	15,773	9,773	27,873	51,350	0.54
S4	7,900	16,492	10,492	28,592	51,350	0.56
S5	7,900	10,756	4,756	22,856	51,350	0.45
S6	7,900	8,412	2,412	20,512	15,800	1.30

Activity II = Measured value – fallout on the reservoir (~6,000 Bq);
Activity III = Activity II + value of the fishpond;
Topsoil = the uppermost 20 cm of the profile).

concluded that during the investigated period (34 years) ca. 435,086 m^3 soil was eroded by gully erosion. One part of the sediment was deposited on the gully's fan, and another part was sedimented on the valley bottom and the rest reached the stream and was deposited in the sediment reservoir.

Comparing the sediment volume in the reservoir with soil loss volume coming from the gullies over the 34 year period it can be stated that about 10% of the soil eroded by gullies reached the outlet of the catchment. Presuming uniform soil erosion and sediment transport this means 1,287 m^3 $year^{-1}$ from a catchment of 120 km^2 which is a potential danger for Lake Balaton. This amount is only the result of gully erosion and the same amount was eroded by sheet erosion.

Conclusions

According to our measurements the majority of soil loss is eroded by sheet erosion in the catchment, but this type of sediment generally does not leave the catchment. The sediments that leave the basin, contain more subsoil, approximately 50% in this case. This fact underlines the role of gully erosion as sediment source and not only as transport channel in the catchment. In addition to this the results show that the activity of gully erosion has a yearly fluctuation on one hand and a 5–10 years periodicity on the other. In general early spring low volume topsoil sediments will be deposited in the reservoir and during the periods of thunderstorms (late summer) a large amount of subsoil is eroded and delivered beyond the limits of the basin. This periodicity can be seen in the stripped profile of the reservoir. According to both gully development and sedimentation, the most active period of "subsoil" sediment transportation occurred between 1984 and 1995 in the catchment.

It is important to decide whether sheet or gully erosion should be controlled to gain the most benefit. Both processes cause damage, control is therefore necessary. The question is efficiency and cost return. Nowadays soil protection has less importance both in policy and in practice in Hungary but in the long run it is necessary to concentrate on soil conservation. For effectivity reasons it is evident that gully erosion control has primary importance. It is not only the source of the sediment but has a key role in transporting soil eroded by sheet erosion.

The best way to stop gully erosion is reforestation of the gully because under forest there is no soil erosion, says the average Hungarian farmer. It could be true in case of sheet erosion, but not in case of gully erosion. It is evident that erosion control (reduction of surface runoff) has to begin in the catchment of the gully first; the neighbouring area of the gully is of secondary importance.

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