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Application of Historical and Recent Aerial Imagery in Monitoring Water Erosion Occurrences in Czech Highlands

Markéta BÁČOVÁ and Josef KRÁSA

[1]*Department of Irrigation, Drainage and Landscape Engineering, Faculty of Civil Engineering, Czech Technical University in Prague, Prague, Czech Republic*

Abstract

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This study is focused on the historical evolution of a heavily eroded field with discontinuous grass cover on a major thalweg (ephemeral gully). Tens of parcels originally formed a protective pattern in the study area, and the thalweg was permanently covered with grass. During the period of collectivization, the field structure had been unified into a compact 34 ha parcel, which resulted in the formation of ephemeral gullies after every heavy rainfall event. Historical and recent aerial photographs were used to analyze the erosion occurrences, vegetation degradation connected with the erosion processes, and the land-use pattern. The visual erosion pattern assessment has indicated that in this field, rills and other erosion objects have repeatedly developed in the same locations in different time periods. The soil erosion hazard was also modelled by the new Czech erosion model Atlas EROZE. A comparison between the modelling results and the assessment of real visual data shows that areas at risk can be identified by both these methods. In addition, the land-use pattern was modelled using two different scenarios. The results suggest that soil erosion can be significantly reduced by segmentation of the field into smaller plots.

Keywords: Atlas EROZE model; erosion modelling; land-use changes; remote sensing; soil erosion

Soil erosion by water is one of the main degradation processes of agricultural land in the Czech Republic. Official data has shown that more than 50% of the soil erosion hazard in the country is from water in rural landscapes (Novotný *et al*. 2014).

The soil erosion processes on agricultural fields were escalated by the collectivization of Czech agriculture during the communist period in the 20^{th} century. During this period, small individual fields were merged into large plots. The traditional Czech agricultural landscape, with its small-scale mosaic of fields attended by protective elements such as strips of bushes, small forests or meadows, completely disappeared. The main goal of the changes was to maximize agriculture production by using heavy agricultural machinery and chemical fertilizers – with no respect for other functional aspects of the landscape.

Many authors have dealt with collectivization in Central and East Europe in relation to the evolution of land use (Bouma *et al*. 1998; Feranec *et al*. 2000; Bičík *et al*. 2001). The influence of this process on the escalation of soil erosion was estimated for example by Stehlík (as cited in Stankoviansky *et al*. 2000). According to Sklenička (2006), changes caused by collectivization led not only to problems with soil erosion, but also to the loss of important small biotopes and degradation of aesthetic values of landscape.

Aerial photographs (used e.g. by Frazier *et al*. 1983; Fulajtár 2001; Maugnard *et al*. 2014) and nowadays also UAV images (d'Oleire-Oltmanns *et al*. 2012; Eltner *et al*. 2015) are the most widely used data sources for monitoring and analyzing single catchments and smaller areas. Erosion pattern assessment and quantification can be done automatically by means of supervised or unsupervised classification (Fulajtár 2001), in some cases using object-oriented analysis techniques (Wang *et al*. 2014). The advantages of automatic classification are time-saving for

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applications in large areas, and the application of exact criteria over entire study areas. However, the accuracy depends on the intensity of erosion effect in the analyzed data. Another possible method for automatic identifying these small erosion patterns is to use the digital elevation model (DEM) obtained from UAV data or from other precise methods referenced below (Eltner *et al.* 2015; Vinci *et al.* 2015).

Recently, a detailed erosion occurrence monitoring directly by elevation models derived by terrestrial laser scanning (Vinci *et al.* 2015), stereoscopic imagery (Bauer *et al.* 2015), and SfM methods (Kaiser *et al.* 2014) has become possible. Unfortunately this type of data is not available for earlier periods and researchers have to rely on aerial photogrammetry and visual data interpretation.

Another way is to compare erosion monitoring data with erosion models (De Jong *et al.* 1999; Mhangara *et al.* 2012). This way, the erosion models can be calibrated and verified. Erosion models (a review of erosion and sediment transport models was published by Merritt *et al.* 2003) can then be used to estimate the effect of different land pattern situations or virtual land protection scenarios. Various scenarios for average field size and for the conversion of selected fields to grassland in the Czech Republic were modelled by Van Rompaey *et al.* (2007) using the SEDEM model.

The aim of the study is to analyze the possibilities of "data mining" in the Czech Republic for estimating the recent extent of erosion not by USLE-based models (usual, widely published approach), but by monitoring the occurrences of actual water erosion.

In the Czech Republic, a project under the title Monitoring of Erosion Events as a web based application was introduced in 2012 by the Research Institute for Soil and Water Conservation and the State Land Office. An expanding database of monitored events is filled in under the supervision of the regional land offices, and nowadays covers more than 550 cases of erosion occurrence (VÚMOP 2015). A field survey is coupled with rain and model data, and will assist in implementing the European Cross Compliance policy in the Czech Republic. Localities with monitored repetitive erosion events can be classified as vulnerable, with obligatory implementation of protective measures within Good Agricultural and Environmental Conditions (GAEC).

In order to investigate the possibilities of a historical review in "vulnerable areas", this study is focused on the availability of recent imagery and on imagery analyses to pair the land-use pattern, occurrences of erosion, rainfall data, and periods of image acquisition within the year to reveal the usability of remote sensing and photogrammetry data for this purpose.

The study is focused in detail on a single agricultural field, where the evolution of the land-use pattern and the erosion effects have been analyzed for the period 2002–2014 and compared with the historical lay-out of the field prior to collectivization. The period since 2002 is used, because by that time the modern era of the availability of orthophotos in the Czech Republic began: digital imagery, higher spatial resolution, and higher temporal resolution (2 years) enable us to examine localities with a higher probability of success in the search for erosion. Older imagery is mostly black-and-white, with limited explanatory power for current vulnerability of the landscape to erosion. A time series of aerial photographs collected for this study was also used for analyzing the landscape evolution of the study area. For this reason, one image from the pre-collectivization era (1953) was added to the collection. In order to contribute to the conclusions with an estimate of the effect of changes in the landscape on erosion, the study area was modelled using the new Czech Atlas EROZE USLE-based model (Kavka *et al.* 2013) for the best-case scenarios and the worst-case scenarios concerning the land-use pattern. The advantage of the selected model (over other USLE-based approaches) is an accurate spatially distributive assessment of contributing areas over the most detailed digital elevation models acquired by laser-scanning (e.g. DMR 5G in the Czech Republic).

MATERIAL AND METHODS

Study area. The experimental catchment of the Býkovický stream is located in the the Central Bohemian Region near the town of Benešov (approximate latitude 49°46'N, longitude 14°50'E), Czech Republic (Figure 1).

The catchment is located in highlands with moderate elevations ranging from 370 to 510 m. The locality refers to the Moldanubian Zone of the Bohemian Massif, and is underlain by granite and diorite rocks. The dominant soil type is Cambisol (covering a large area of the Czech Republic), according to the official system of Valuated Soil Ecological Units (BPEJ) the main soil units of the area are 29 (Eutric Cambisol) and 50 (Stagno-gleyic Cambisol). The topsoil reaches to a depth of 40 cm. According to a particle size

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analysis, the upper horizon consists of sandy loam with stoniness (up to 25%).

The average total annual precipitation in the study area is 600–700 mm, and the average annual temperature is 7–8°C (Tolasz *et al*. 2007). In the Czech Republic most of highly erosive storms usually occur in June, July, and August (Kubátová *et al.* 2009).

The study area is a single agriculture field, 34.1 ha in size. The average slope steepness is 9.2%, but the morphology of the slope is quite heterogeneous (Figure 1). The field is diagonally divided into two parts by one major thalweg: the western part has a convex longitudinal profile and contains several minor thalwegs, while the eastern part has a

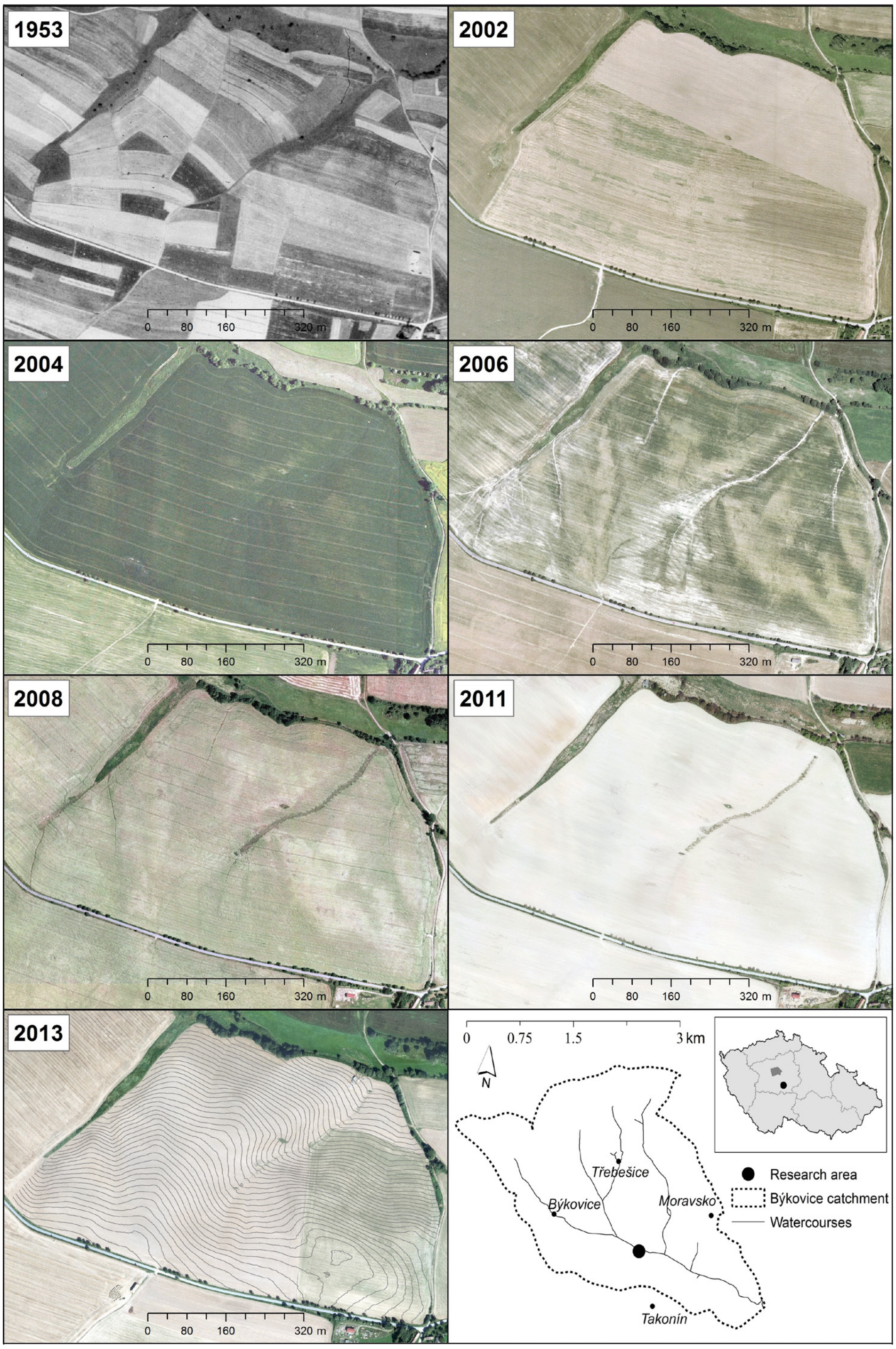

Figure 1. Time series of aerial photographs of the study area; location of the study area (bottom right)

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combined convex-concave profile and contains one minor thalweg.

In 2009, three USLE plots (22.13 × 2.27 m) and one plot comparable with the laboratory rainfall simulator at the Czech Technical University in Prague (4.0 × 0.9 m) (Bauer *et al*. 2014) were installed in the north-eastern part of the field. These plots are equipped with measuring device for obtaining and recording meteorological data together with the water and sediment runoff from the plots (Davidová *et al*. 2015). Both meteorological data and sediment yield obtained from long-term measurements were used for a comparison with situations captured in the aerial photographs.

Data sources. For this study, very high-resolution satellite images (Pléiades, QuickBird, WorldView-2, and GeoEye-1) were obtained and considered. However, this spatial resolution is still in most cases by at least 50% lower than the resolution of the aerial photographs, especially recent aerial photographs. For this reason, and also because of the high cost of satellite data, only aerial photographs were used for a detailed assessment of the erosion damage in the field.

Multi-temporal aerial photographs of the study area were obtained from two available archives in the Czech Republic – the Czech Office for Surveying, Mapping and Cadastre, and the private company GEODIS BRNO. The resolution of the photos is from 0.5 to 0.125 m, depending on their age. Six photographs from the recent period were used to analyze the detected erosion objects and the condition of the thalweg, and one photo from 1953 (archive of GEODIS, original data of the Czech Army Military Geography and Hydrometeorology Office) was chosen for the analysis of the land-use pattern in the pre-collectivization period.

Precipitation data for the study was obtained from the Czech Hydrometeorological Institute (CHMI). The nearest precipitation station is located in the village of Postupice, approximately 5 km to the southwest of the research area. The time series of precipitation data from this station is available from 1961 onwards, which does not cover the year 1953, i.e. the first year of our observations. In 2010, a research precipitation station was installed in the study area by the USLE plots. Data from this station (Bauer *et*

Table 1. Characteristics of erosion objects in the study area

Date of orthophoto	Research area conditions	Thalweg			Minor rills		
		conditions	average width (m)	area (m)	conditions	average width (m)	length (m)
10. 8. 1953	ca. 45 plots with varying condition of vegetation	grass cover; rural road stretching in S part	32.7	11 244	land boundary placed in the rill channel on SW edge of field	–	–
21. 7. 2002	bare soil in N part; ripening vegetation in S part	barely visible; ploughed under	–	–	one indistinct rill	–	137
29. 5. 2004	vegetation cover	barely visible; ploughed under	4.7	3 291	barely visible	–	249
18. 7. 2006	vegetation cover; degradation by sheet and rill erosion	distinct; soil and vegetation loss; minor rills extension in S part	4.6	2 735	distinct rills and ephemeral gullies formed after the rainfall event	3.3	1 148
6. 7. 2008	vegetation cover	distinct; grass cover; extension of minor rills in S part	10.4	4 812	distinct rills with different condition of vegetation	2.8	911
23. 4. 2011	bare soil	distinct; grass cover; grassless extension in S part	8.8	3 693	–	–	–
6. 9. 2013	crop residues; ripening corn in W part	indistinct; grass cover in narrow band	7.8	3 523	barely visible	–	182

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al. 2014) has been coupled with observations from recent aerial photographs.

Historical evolution of soil erosion objects in the study area. All aerial photographs were georeferenced and analyzed using ArcGIS software (Ver. 10.2.1, 2013) (Figure 1). The comparison focused on main indicators of soil degradation by erosion on this field: first, the major thalweg; second, the minor erosion rills or ephemeral gullies formed on the western and northern border of the field, and the other rills leading into the major thalweg.

The erosion objects observed in the aerial photographs were identified by visual inspection over multi-imagery scenes. Visibility was aided by contrast enhancements of the scenes and by Laplacian Edge Detection as a support analysis. Cluster analyses (object classifiers) were not fully successful due to different patterns in different time periods of image acquisition. Supervised classification methods were tested for the investigation of the locations of sheet erosion, and were coupled with slope steepness layers and contributing area layers (flow accumulation thresholds). These approaches were published by Kavka *et al.* (2014). Finally, visual interpretation was selected as the best estimator for this study in the detailed scale.

The observed erosion objects were digitized (Figure 3), and their condition and dimensions were calculated and tabulated (Table 1), together with the exact dates on which the aerial photographs were taken. In this way, a comparison could be made between the situation in the photographs and the amount of precipitation measured in previous months. The total precipitation amount in each month was calculated from the daily precipitation values. Rainfalls amounting to more than 12 mm were separated to approximate the threshold for erosive rainfall according to the Wischmeier R-factor derivation method. This precipitation data is summarized in Figure 2.

Soil erosion modelling. Soil erosion modelling was implemented in the study to illustrate the effect of changes in the landscape pattern on the total soil loss from the area. The modelling was therefore performed for the best-case scenario and the worst-case scenario as regards the land-use pattern. Year 1953, with 45 parcels in the field, was selected as the best-case scenario. Year 2006, when there was a single parcel with no protection in the thalweg, was selected as the worst-case scenario. The Czech model Atlas EROZE, developed as a tool for land management planning, was applied. It uses a unique 3D USLE approach: the sediment is routed directly on a detailed laser scan TIN terrain model. LS factor 2D implementation proposed by Desmet and Govers (1996) and Nearing's (1997) S factor formulas are used. We used information provided by farmers about the typical crop rotation for the area. The resulting average C factor was 0.32 (spring barley, rye, potatoes, winter wheat, and tripholia). The long term average R factor was 62 N/h/year. The average annual R factor (35–80 N/h/year) was derived from the long-term R factor distribution map for the Czech Republic (Krása *et al.* 2014). The K factor of Cambisols of the field varies from 0.16 to 0.49 t/N (0.26 t/N on average). It was derived from soil bonity vector maps (BPEJ) on a 1 : 5000 scale, using the official relation of Vopravil *et al.* (2007). Apart from the land-use pattern, all parameters were kept constant for different time periods in order to address directly the influence of landscape variability.

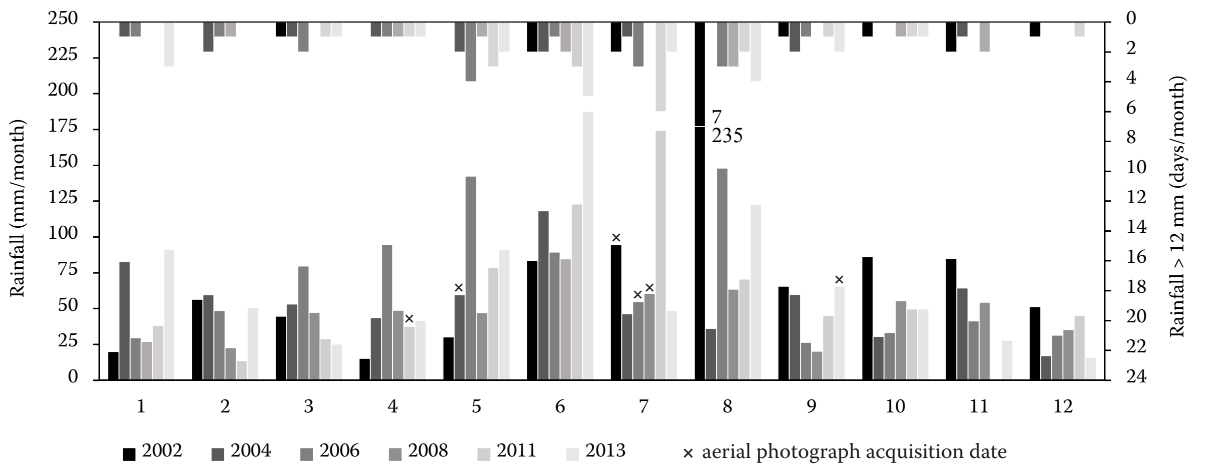

Figure 2. Precipitation amounts and numbers of erosive rainfalls for individual months

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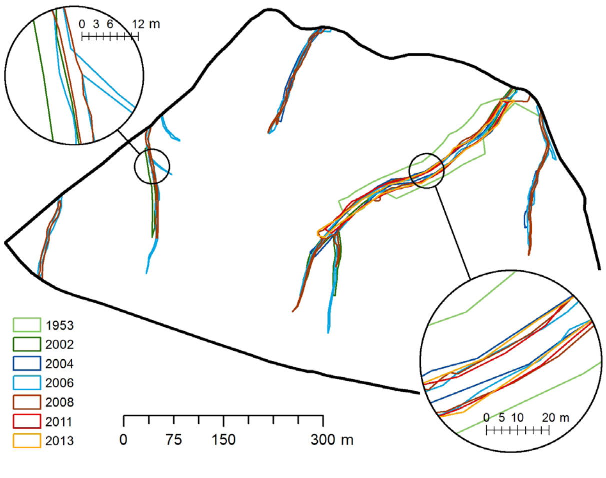

Figure 3. Digitized erosion objects in the study area (major thalweg and minor erosion rills) and their changes in size over time

RESULTS AND DISCUSSION

Evolution of land-use and erosion objects. The most noticeable change in the study area is that in land use between 1953 and recent years (Figure 1). In the 1953 historical photograph 45 plots are observable, while recent images show maximally two. The land consolidation from the communist collectivization period led to destruction of the protective pattern of small fields (see the results of modelling).

Over the decades, a major ephemeral gully has formed in the same location on the field (Figure 3). Its formation was determined naturally by geomorphology of the field. However, there is heterogeneity in the land use, in the character of the soil degradation, and also in the dimensions of the gully (Figure 4 and a detailed description in Table 1). Originally, the thalweg was not cultivated, and it was protected by an approximately 33 m wide strip of grassland. In the southern part of the field, a rural road passed by the thalweg and continued on to the southern ridge. In the following photographs (2002, 2004), the grass protection of the thalweg is missing, and the thalweg was ploughed, together with the surrounding land. This probably accelerated the extensive soil degradation by erosion that can be observed in the picture from 2006. An extreme volume of soil was transported from the location of the originally grassed thalweg, and an ephemeral gully with an average width of 4.6 m was formed. The central thalweg was overgrown again by about a 10 m wide grass strip between 2006 and 2008. However, the grass-covered strip got narrower later on, probably due to gradual ploughing of the soil as far as the edge of the grass. As a consequence, the protection provided by the thalweg has decreased. The study area has nearly no bottom sedimentation zone, the field is characterized by a uniform slope down to the lower edge (Figure 1), crossed by the Býkovický stream in a V-shaped 2-m deep profile. Only the lowest field area directly surrounding the main thalweg (ca. 20 × 50 m) regularly shows shallow sand deposits from erosion events. The sheet erosion probably usually redeposits at the field but the material transported by monitored rills can be considered as a sediment yield and is washed out from the field to the Býkovický stream. At the convolution of the major thalweg and the stream profile an open gully (cavern) disrupted the stream bank and rises up the field. The erosion sedimentation pattern is not directly recognizable from the orthophotos and is not within the scope of this study.

In the study area, also minor rills and ephemeral gullies forming in the same position in each period are observable. These rills are not obvious in the historical photograph, but the boundary between the small plots in the south-western corner is located exactly in the position of the minor rill in later years. In this way the rill was naturally kept free of farming. The minor rills can be observed in the pictures since 2002, when one indistinct rill was identified. In 2004 there were already two minor rills located in the northern part of the study area. However, these minor rills are again only barely visible and their width is unmeasurable. The minor rills are easily recognizable in 2006, when at least six ephemeral gullies can be found, with an average width of 3.3 m. Formation of these rills can also be observed in other recent pictures, though they are less distinct.

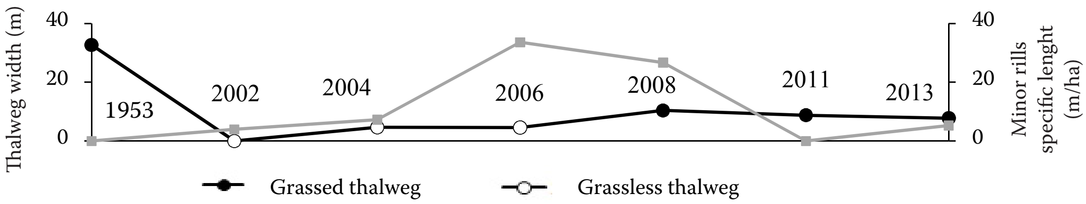

Figure 4. Changes in width of the thalweg and in specific length of minor rills over time

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Four rills with an average width of 2.8 m are visible in the orthophoto from 2008, and two minor rills of unmeasurable width can be barely identified in the orthophoto from 2013. A detailed description of the minor rills is provided in Table 1. The highest value – 1148 m of total length (33.6 m/ha) of assessed rills was registered in 2006. The length of rills in 2008 is similar (911 m in total, 26.7 m/ha of specific length), but the extent of these rills is different, they are characterized by a different condition of vegetation, not by visible soil loss like in 2006. The measured length of rills identified in other years is approximately 5–8 times lower than in 2006, it ranges between 137 and 249 m in total which means 4–7.3 m/ha of specific length. The evolution of the rills length is presented in Figure 4, where the peak of specific length in 2006 and 2008 is obvious.

Data obtained from long-term measurements in the experimental plots (Bauer *et al.* 2014) was used for a comparison between the real measured episodes on the field and the situation captured in the aerial photographs in relevant periods. Due to the installation of the plots in 2009, data can be compared only with those yielded by images from two years (2011 and 2013).

In 2011, eight erosive rainfalls were recorded, with a total precipitation amount of 207 mm. This caused a soil loss of 225 kg from the 50 m^2 Wischmeier cultivated fallow plot (45 t/ha/year). However, the picture from 2011 was taken at the end of April, so any significant rainfall before this date is not recorded in our measurements. According to data provided by CHMI, only two erosive rainfalls with total amounts of 16.2 and 14.1 mm were observed at the precipitation station near the site. For this reason, there are more or less no erosion effects in this picture.

In the 2013 season, only three erosive rainfalls were recorded, with a total precipitation amount of 134 mm leading to the transport of 35.9 kg soil (i.e. 7.2 t/ha/year) from the experimental plot. This volume would correspond to soil loss of 250 t/year from the whole study area for a cultivated fallow. More erosion objects can be observed in the aerial photograph taken in September, but none of the rainfall events was so significant to form such an extreme volume of rills as in 2006.

The photographs from the other years could not be compared with our own measurements from the research area. However, in 2006 intensive rainfalls can easily be identified in the data from CHMI, and these probably caused the extreme degradation of the field. In May 2006, there were four erosive rainfalls with a maximum precipitation amount of 34 mm per day and a total volume of 95 mm. In June 2006, only one intensive rainfall was recorded – but with a total precipitation amount of 54 mm. These extreme events resulted in significant soil degradation due to rill erosion, ephemeral gullies, and sheet erosion throughout the study area, as it was described above.

Soil erosion modelling. For typical crop rotation and rain erosivity settings, the average soil loss for the whole field calculated for 1953 was 5.6 t/ha/year. For the same settings in 2006, the value rose to 12.8 t per ha/year (a total of 443 t per the whole field). This indicates that the segmentation of the farmland into a mosaic of fields (state by 1953) led to a 56% reduction in soil loss. The grass-covered thalweg and the six small meadows within the study area contributed to this reduction by 7%.

These results, showing the impact of land consolidation on the soil loss, correspond to the results reported by other authors. For example Golosov and Belyaev (2013) published results for the relative intensity of soil erosion measured in the Zusha River basin, located in the main agricultural region of European Russia. In that area, the intensity of sheet and rill erosion reached its maximum after the collectivization in 1938. Stankoviansky (2000) evaluated the effects of collectivization from a complex viewpoint using rule-based GIS modelling. His results from the Jablonka catchment for example show an increase of areas with a high or very high degree of susceptibility to erosion processes by about 40% in comparison with the pre-collectivization period.

The results of the soil erosion modelling in the study area are shown in Figure 5. It is also apparent that the local maximum of soil loss, modelled under the 2006 conditions, was six times higher than the local maximum of soil loss modelled under the 1953 conditions. A concentrated flow did not appear in the 1953 model if compared to the 2006 model. Concentrated flow paths were modelled in the 2006 scenario exactly in the locations where the rills were identified from recent aerial photographs. The identified rills from recent years were also compared with the 1953 scenario. The location of rills is especially in the western part of the field identical with the location of boundaries between the plots in 1953. The area of the main thalweg was covered with grass in 1953.

For the seedbed conditions scenario, the model computed even a high average soil loss for the field – 40.1 t/ha/year under 2006 conditions. This corresponds to the values measured by the Wischmeier

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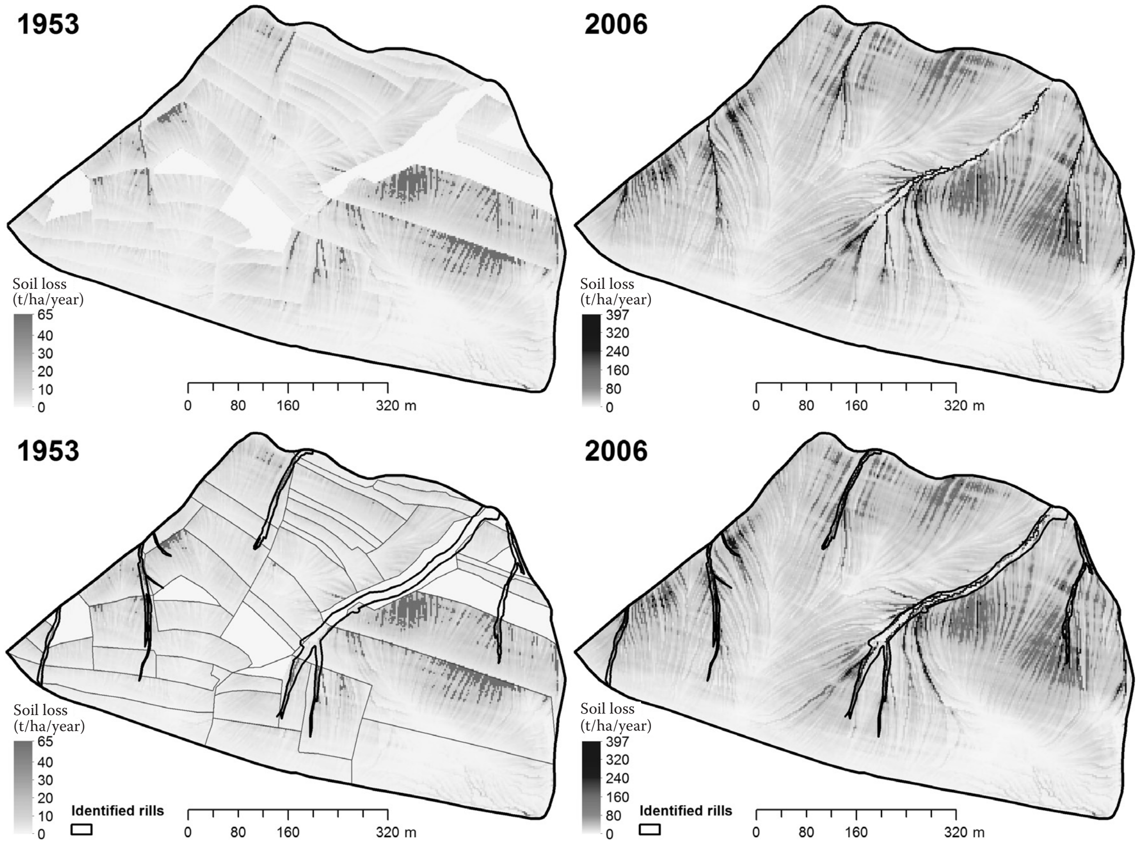

Figure 5. A comparison of the modelled soil loss on the field in 1953 and in 2006 (top); a comparison of all identified rills in recent years with the results of modelling from both years (bottom)

plots in the same condition in 2011 (45 t/ha/year), knowing that the average slope steepness of the whole field is 5.27° (9.2%).

Based on the recent, rather high rainfall erosivity of the location, the modelled average soil loss even for the fragmented landscape pattern (1953) was more than 5 t/ha/year. The reason is that even in the 1950s the field was mostly used for seed and potato production, while the average slope steepness exceeded 10% on most of the area. The lengths of slopes varied, being close to 100 m in several plots. Single parcels were strictly contour-oriented and under less intensive tillage technology used in the pre-collectivization period the values were probably lower than the modelled. However, despite the high soil loss the sediment yield was reasonably reduced by the permanent grass cover in the wide thalweg zone and by the pattern of country lanes crossing the field.

CONCLUSION

In this study, the land-use pattern and erosion features evolution in a typical highland parcel was analyzed using a time series of aerial orthophotographs. The detailed analysis was focused on the period 2002–2014 as well as on the comparison with the condition of the locality in 1953, before the collectivization, when the field consisted of 45 plots and the central waterway (thalweg) was protected by a permanent grass cover.

Soil erosion features have been identified in most of the obtained aerial photographs. They have reappeared in identical locations, but differed in character and intensity. The largest erosion damage was observed in the picture from 2006, where the average width of ephemeral gullies reached 3.3 m, their total length was more than 1 km, and soil loss was significant on the entire field including the thalweg. The total length of detected minor rills was by approximately 5–8 times lower in other periods, except for the year 2008, when it was similar with that of 2006. However, the condition of detected rills was different.

A massive erosion after the heavy rains in 2006 led to reintroduction of the permanent grass cover (of very limited width) of the main thalweg. However, in

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the following years (2013) the thalweg was ploughed again to maximize short-term agricultural profit.

The lay-out of the field has unfortunately stayed similar like right after the collectivization. Though, the results of modelling demonstrated that the segmentation of the field to the small parcels positively influenced the soil erosion conservation. When the detailed landscape mosaic (45 plots seen on the 1953 photo) was merged into a single parcel and the thalweg was ploughed, the calculated average soil loss increased more than twice (from 5.6 to 12.8 t/ha/year).

The results from modelling were compared with the results from the visual assessment of real erosion objects detected in aerial photographs. It was found out that the paths of concentrated flow predicted by the model are located in identical positions as the rills digitalized from the photos. The comparison has shown that parcels highly vulnerable to soil erosion can be evaluated using a time series of officially available orthophotographs enabling to detect locations at the highest risk. We may conclude that the USLE 2D based modelling over detailed LIDAR DEM is a suitable tool for completing the monitored data by numerical values of long term average soil loss.

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Corresponding author:

Ing. Markéta Báčová, České vysoké učení technické v Praze, Fakulta stavební, Katedra hydromeliorací a krajinného inženýrství, Thákurova 7, 166 29 Praha 6-Dejvice, Česká republika; e-mail: marketa.bacova@fsv.cvut.cz