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Causes of Water Erosion and Benefits of Antierosion Measures in Model Locality Starovice – Hustopeče (South Moravia Region, Czech Republic)

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ABSTRACT

The agricultural land found in the Czech Republic is strongly degraded by water erosion. The main reasons for this situation are the changes in the landscape caused by large-area agricultural production in the second half of the 20th century. In the model locality Starovice – Hustopeče (223.5 ha) (South Moravia Region), we analysed the changes in the landscape structure and land use for the period 1825–2018. In 1825, the mean size of a land block was 0.4 ha. In 1968, the studied locality consisted of just one land block of a size of 223.5 ha. This period marks the beginning of massive water erosion. In 2003, the locality was proposed for land consolidation. Its goal was to reduce erosion and the risk of floods. To date, a number of protective measures have been applied in the locality. The risk of water erosion was assessed for the landscape state in 1968 and 2018 in GIS using the USLE method. The effect of the adopted measures was strongly manifested in the reduction of the erosion risk (by 44%). The transport of sediment out of the locality was assessed for 1968 and 2018 by means of the WaTEM-SEDEM model. The protective measures resulted in a decrease of sediment transport out of the locality by 111 t/year (40% reduction). The economic balance of the soil loss showed a positive impact of the applied protective measures. On the basis of the mean price of arable land in the Czech Republic and the costs of the soil relocation within the locality, the application of protective measures brought an economy of at least € 5,000 per year. This sum does not include the losses caused by a potential decrease of agricultural crop yields due to the soil degradation, reduction of ecosystem services, and other factors in the past years. The actual benefits of applying the protective measures aimed at reducing erosion and increasing water retention in the landscape are significantly higher.

Keywords: water erosion; land consolidation; land use; historical maps; GIS; WaTEM-SEDEM

INTRODUCTION

The loss of high-quality agricultural land is perceived worldwide as an extensive problem touching not only the developing countries. The main threat to the environment and agriculture is water erosion (Pimentel et al., 1995). Soil erosion is a natural process, which is accelerated by insensitive interventions of man into the natural environment and landscape and by intensive management of agricultural land. This phenomenon is defined as a process of release, transport and deposit of soil particles by flowing water (Lal, 2001). In association with the ongoing climatic change, more frequent occurrence of extreme precipitation is expected in Europe (Walling, 2009). This extreme precipitation directly induces erosive processes and risk of local floods. The consequences of these erosive processes are manifested both directly (on site) by crop losses and indirectly (off site) as sedimentation effects.

In the Czech Republic (CR), water erosion potentially threatens almost 50% of the agricultural land, 18% of which is at extreme or high risk; about 20% is at risk of wind erosion, almost 5% of which at extreme or high risk (Dostál et al., 2006, Podhrázská et al., 2015). Erosive processes, their consequences and methods of evaluation (modelling) were investigated both in CR and worldwide by a number of authors. The most popular method of water erosion risk modelling is represented by the empiric equation "Universal Soil Loss Equation" (USLE) (Wischmeier, Smith, 1978). Interpretation of the universal equation factors in the conditions of CR was done by several authors, and USLE was applied to the conditions of CR by Zdražil (1965), Holý (1978, 1994) Pasák (1984), Toman (2000), and Janeček et al. (2012). The USLE equation served as a basis for the WaTEM/SEDEM model (Van Rompaey, Krása et al., 2015), allowing not only the assessment of the water erosion risk in a locality, but also of the volume of sediments exported out of the investigated locality (catchment) and the volumes that have been eroded but remain accumulated at the base of the slopes.

The main reasons of the high erosion threat in CR were insensitive human interventions into the landscape in the second half of the 20th century. Until this period, the agricultural production exploited land blocks of a mean size of 0.5 ha. The main efforts of the Socialist regime were focused on intensifying the agricultural production. The agricultural production was collectivized and large agricultural cooperatives were established. The landscape was subjected to extensive devastation of natural eco-stabilizing elements, destruction of spinneys, balks, drainage of river floodplains and wetlands. Large land blocks of hundreds of hectares in size were created. These factors led to a massive development of wind and water erosion and to the problems of low water retention in the landscape, with flash floods from heavy rainfalls (Thomas, 2006; Hartvigsen, 2014). However, after the changes in the political regime, the situation in the agricultural system of land farming did not improve. Most of the agricultural land is rented (approx. 80 %) and farmed in large blocks, with monocultures of marketable crops (maize, rape, wheat). At present, the maximum soil loss in CR is estimated to be approximately 21 million tons of arable land per year, which may be expressed as an economic loss of CZK 4.3 billion per year (Podhrázská et al., 2015).

The changes in the landscape are mostly documented in archived materials (historical maps – in particular, maps of the Stable Cadastre dating from the middle of 19th century and historical aerial photos from the 20th century). They provide precious information on the development of land use / land cover in the country) (Stejskalová et al., 2013, (Szturc et al., 2017).

Unfortunately, the current poor situation of agricultural landscape is not particularly interesting for large agricultural subjects – land renters, who prefer short-term economic profit to permanently sustainable development of rural areas. Virtually, the only existing tool to improve this situation is land consolidation, adjusting the property rights in the public interest while proposing and implementing the measures serving to protect and rationally utilize natural resources (soil, water) for the development of rural areas. Land consolidation consists in proposals and subsequent implementation of antierosion, water management, and ecological measures in the landscape. It is a long-term process of gradual "stabilization" of the Czech landscape to a regime of permanently sustainable management. The process of land consolidation in CR, as it is known today, has been adopted since 1991 and is currently controlled by the State Land Office (SLO). Land consolidations are regulated by Act No. 139/2002 Coll. The law stipulates that land consolidations create the conditions for rational management by landowners, improve environmental protection and water management (Karásek et. al, 2018). The costs of implementing the anti-erosion and water-management measures are high. Nevertheless, in the long term, the positive effects on the landscape, soils, and water retention exceed the input costs. As reported by Konečná et al., 2014, long-term economic analyses showed that prevention of the negative effects of soil and water degradation are more advantageous than solving their consequences.

In this report, we wanted to identify the causative factors of massive erosion in the model locality Starovice – Hustopeče u Brna and to evaluate the benefits of the adopted antierosion and water-management measures. The results of this study should bring better insight into the positive effects of appropriately executed antierosion protection in the localities threatened by erosion.

METHODOLOGY AND DATA

Model locality Starovice – Hustopeče u Brna

In order to analyse the temporal changes of land use and erosion caused by intensive management, we selected a model locality in the region of South Moravia. This locality is characterized by the soils with high productive quality and frequent occurrence of water erosion. The locality is represented by a land block (Fig. 1) situated at the borderline of cadastral areas between Starovice and Hustopeče u Brna. From the climatic aspect, it belongs to the warm zone; warm and dry area with mild winters and relatively short sunshine. The parental substrate in the main part of these soils is represented by loess. The loess and the mixed substrates gave rise to Haplic Chernozems, Calcaric and Arenic. The analyses of the erosion risk were done at the land block that by its nature (block size, sloping, type of management) belongs to typical localities with intensive agricultural management in South Moravia. The locality is situated at the altitude of 228 m, with 223.5 ha surface, and its average slope is 7%.

Assessment of changes in land use

Spatial grid data were used as a basis for research utilizing maps (historical maps and current orthophoto maps) provided by the State Administration of Land Surveying and Cadastre and also the Military Geography and Hydrometeorological Office in Dobruška (historical aerial photography). All spatial data was processed by ArcGIS for Desktop 10.5 software developer by ESRI. The data source of historical land use was represented by digitized maps of land use from 1825 (historical maps of Stable Cadastre), 1836–1852 (historical maps of 2nd military mapping), 1876–1878 (historical maps of 3th military mapping), 1938 (aerial images), 1953 (aerial images), 1968 (aerial images), 1950 (aerial images), 1982 (aerial images), 1990 (aerial images) and 2018 (orthophoto). The selected time horizons for the landscape analysis were set up to cover the most important changes in the landscape structure from the beginning of the 19th century to the present. The aerial photos from 1938, and partially also from 1953, show a varied landscape structure of small fields. Arable land may not always be distinguishable from permanent grasslands on the black-and-white aerial photos. Therefore , the assessment of the land use on these temporal series may not always be absolutely precise.

Assessment of erosion risk and sediment transport

The USLE equation was applied in the ArcGIS for Desktop Advanced 10.5. This method allows investigating the entire surface of the land block.

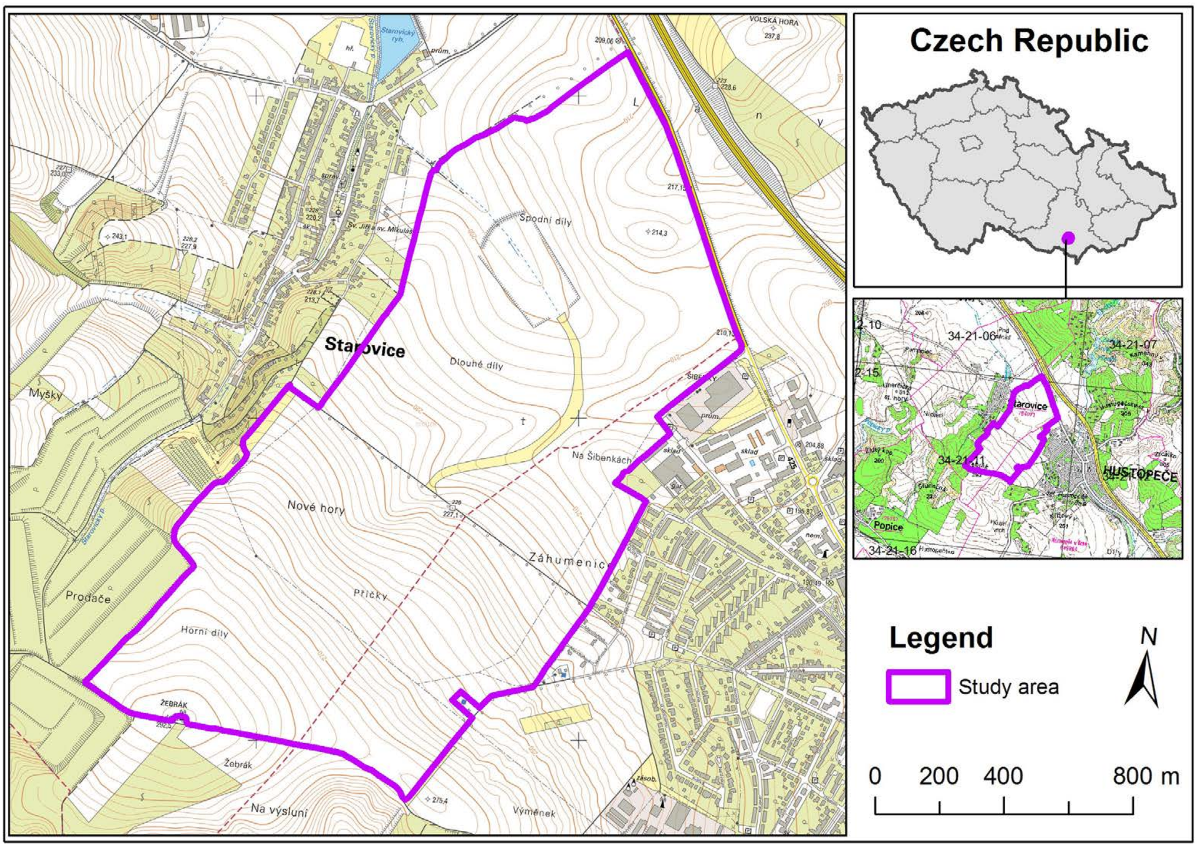

Fig. 1. Location of the study area Starovice – Hustopeče (South Moravia Region, Czech Republic)

The individual factors of the universal equation were calculated according to the currently valid methodology in CR (Janeček et al., 2012). The following values of individual USLE equation factors were established for the investigated locality:

The R factor was set according to the methodology valid for the Czech Republic (Janeček et al., 2012): R=40 $MJ.ha^{-1}.cm.\ h^{-1}$.

In order to establish the K factor, we may use the information on soil characteristics. Vopravil et al. (2011) assessed the individual equation components for the calculation of the K factor of soil samples according to Wishmeier-Smith (1978). For the study purposes, the K factor was established according to the soil characteristics defined during the land evaluation done in 1978 (used for erosion evaluation in the 1968 time period) and after updating in 2013 (used for erosion evaluation in the 2018 time period).

Calculation of the LS factor was performed in USLE 2D (Routing Algorithm – Flux Decomposition, LS Algorithm – McCOOL) (Van Oost, K. et Govers, G. 2004). The data layer was prepared from the raster layer of the digital terrain model (DTM) and the raster layer of land blocks (according to the register of the Land Parcel Identification System (LPIS) database accessible at the website of the Ministry of Agriculture CR – for the present time; for historical time periods, we used historical aerial photography).

The C Factor was determined by assessment of the dependence of the structure of cultivated crops, and thus of the annual value of the C factor, on the climatic conditions of the region according to Kadlec and Toman (2002) as C = 0.307 for the locality Hustopeče-Starovice. For permanent grassland, grassed thalweg, and retention belt we used C = 0.005.

The P Factor was set to the value = 1 (no anti-erosion measures in 1968) and 0.8 (management of the land plot in the direction of contour lines in 2018).

In order to calculate the mean long-term transport of sediment to the closing profile of the study area/catchment, we used the WaTEM/SEDEM software. The model utilizes the revised universal RUSLE equation to calculate the mean annual soil loss. When working with the WaTEM/SEDEM model, we used the same input data as for the USLE model. The calculation algorithm for factor LS utilized McCool, PTEF coefficients (arable land = 0; forest = 75; permanent grasslands = 75), and parcel connectivity for arable land = 40 and for the forest/pasture transition = 75. We used the coefficients of transport capacity (cTc) cTc low = 100, cTc high = 200 (Krása et al., 2015).

RESULTS

The results of our analysis of changes in the landscape structure in nine temporal series show essential transformation in the management of agricultural land. During the entire studied period (1825–2018), arable land prevailed in the locality, but the major difference consists in the size of land blocks. Until 1938, these land blocks displayed narrow elongated forms of small sizes, around 0.4 ha (see Fig. 2). After collectivization of agricultural production following 1948, the agricultural management was dramatically changed in the former Czechoslovakia. Extremely large land blocks were formed by ploughing up the balks and green vegetation in the landscape in order to maximize the agricultural production. In 1825 (according to the analysis of the Stable Cadastre map), the study area contained 548 land blocks of a mean size of 0.4 ha. In 1968, the entire area was already ploughed up to one extremely large land block of a surface area of 223.5 ha. The unfavourable type of land management remained even after the change of the political regime in the 1990s. However, after 1989, an extensive transformation of the legislation resulted in changes in the property rights to agricultural land. Act No. 229/1991, and later Act No. 139/2002 Coll., started the process of land consolidation, which also includes the anti-erosion protection of agricultural land.

In the study area, land consolidation was started in 2003. Its goal was to resolve the problems associated with extreme erosion and flash floods threatening the built-up area of municipalities Starovice and Hustopeče near Brno. The proposal of the land consolidation comprised a system of anti-erosion and water-management measures (1x grassed thalweg, 1x diverting contour furrow, 5x retention grass belts, dry retention reservoir). The total surface area of the proposed grassing was about 16 ha. These measures were adopted during the years 2007–2018. The present state of the implemented measures is shown in Fig. 3. In 2007, the dry retention reservoir and the diverting contour furrow were completed, followed by the grassed thalweg and retention grass belts oriented in the direction of contour lines executed in the years 2015–2017.

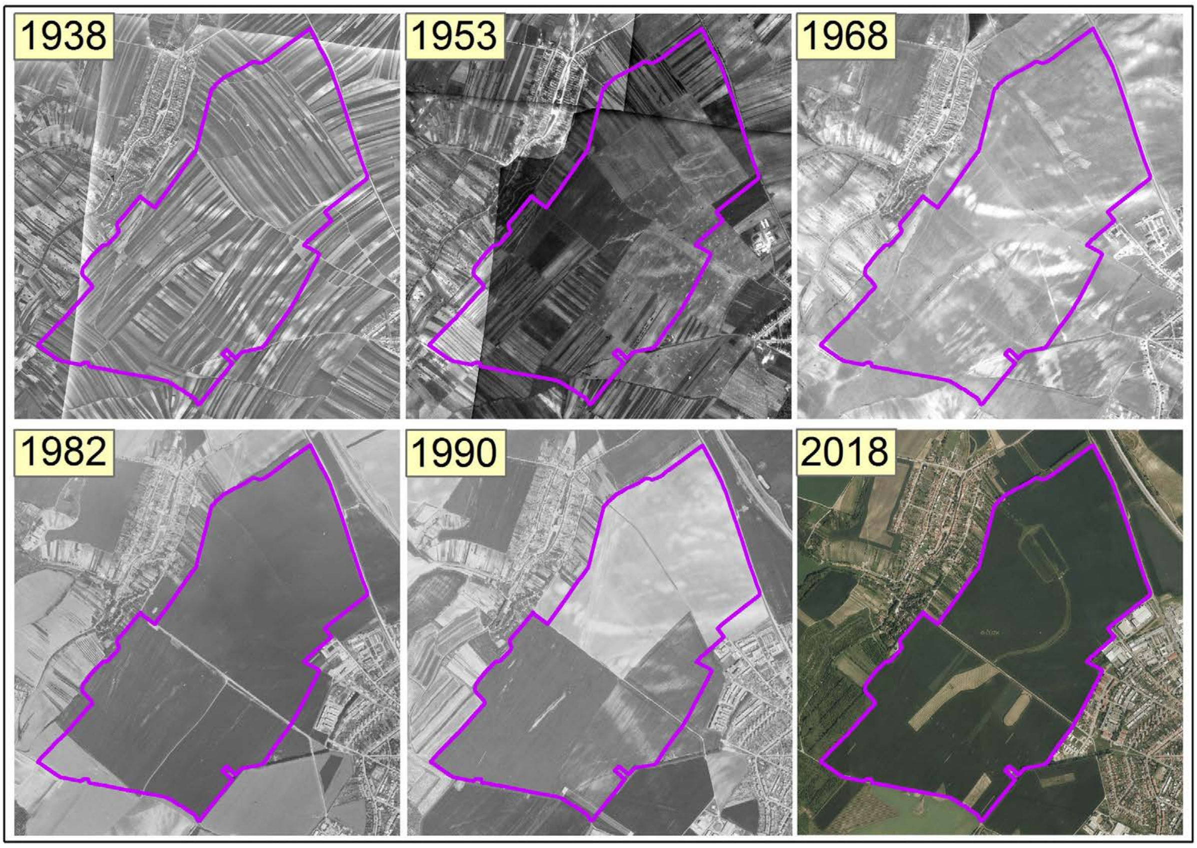

Fig. 2. Aerial photos of the study area in the analysed time period

Application of these measures significantly reduced the erosion risk at the locality. They resulted in an increased retention of the rainfall water and a harmless capture of the surface runoff in the retention reservoir.

In 2018, the study area contains about 16 ha of permanent grasslands. They fulfil the antierosion, water-management, and eco-stabilization functions. Historically, the locality also included vineyards and orchards; however, they gradually disappeared until 1938 and were replaced by the agriculturally exploited land.

The erosion risk was analysed in the study area at two states of the landscape – before implementation of the measures proposed in the land consolidation and after their implementation. The state before implementation of the measures was determined as the state in 1968, because since that period until 2007, the model locality has been, almost without changes, intensively managed as arable land. The results were confronted with the present state (2018), after implementation of anti-erosion and water-management measures. The mean long-term soil loss by water erosion was calculated using the universal soil loss equation (USLE) (Fig. 6).

The resulting values of erosion risk are significantly higher for the time period of 1968, when the processes of water erosion were extremely accelerated. The application of protective measures included in the land consolidation helped to achieve partial reduction of the erosion risk. In 1968, the mean long-term soil loss by erosion was 16.5 t/ha/year. However, at 24% of the study area (54 ha), it exceeded the values of the mean long-term soil loss of 20 t/ha/year. At present (2018), thanks to the application of the protective measures, the risk of water erosion was reduced to a mean value of 7.2 t/ha/year. Specifically, the localities with extreme values of soil loss are now protected. The permissible limit for soil loss by erosion valid at present in CR is 4 t/ha/year (Janeček a kol., 2012). However, in 1968, about 20% of the study area was not at risk of erosion (erosion was lower than the permissible limit of 4 t/ha/year). The remaining 80% of the area was threatened by erosion. At present, 30% of the surface of the study area is not at risk of erosion, but in 70% of the study area, erosion still exceeds the limit values.

Extreme erosion is also documented in Figure 7, showing the southern part of the study area. The soil surrounding a power line pole shows the

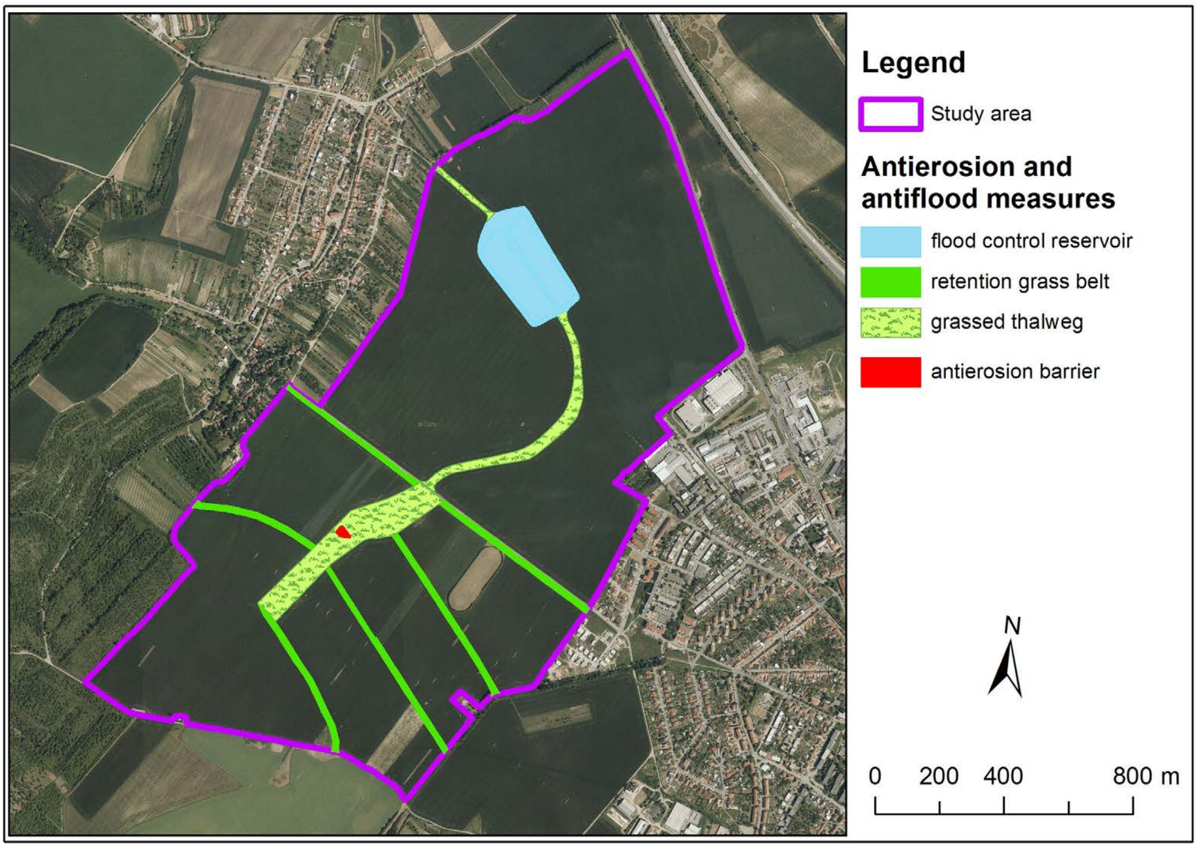

Fig. 3. Application of anti-erosion and water management measures at the study area (state in 2018)

Fig. 4. The present state of the study area (top left – grassed thalweg and retention belt, top right – aerial view of the grassed thalweg and retention belts, bottom left – grassed thalweg, bottom right – grassed thalweg and anti-erosion barrier)

Table 1. Land use in time periods from 1825 to 2018

Land Use	1825	2mm (1836–1852)	3mm (1876–1878)	1938	1953	1968	1982	1990	2018
Arable land	199.0	175.4	163.5	218.9	223.5	222.9	222.9	222.9	207.2
Permanent grassland	10.9	0.4	1.3	0.0	0.0	0.0	0.0	0.0	15.7
Other (field roads)	0.0	0.0	0.0	4.6	0.0	0.5	0.5	0.5	0.5
Orchards, vineyards	13.6	47.7	58.6	0.0	0.0	0.0	0.0	0.0	0.0
Total	**223.5**	**223.5**	**223.5**	**223.5**	**223.5**	**223.5**	**223.5**	**223.5**	**223.5**

*mm is short for military mapping

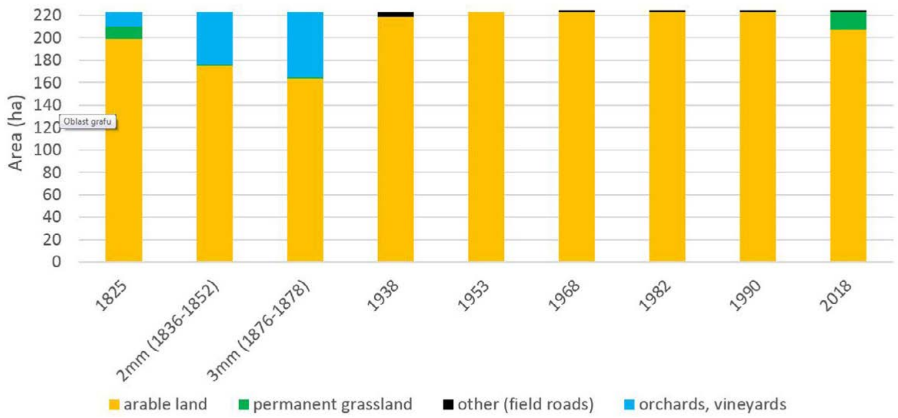

Fig. 5. Land use in the time periods from 1825 to 2018

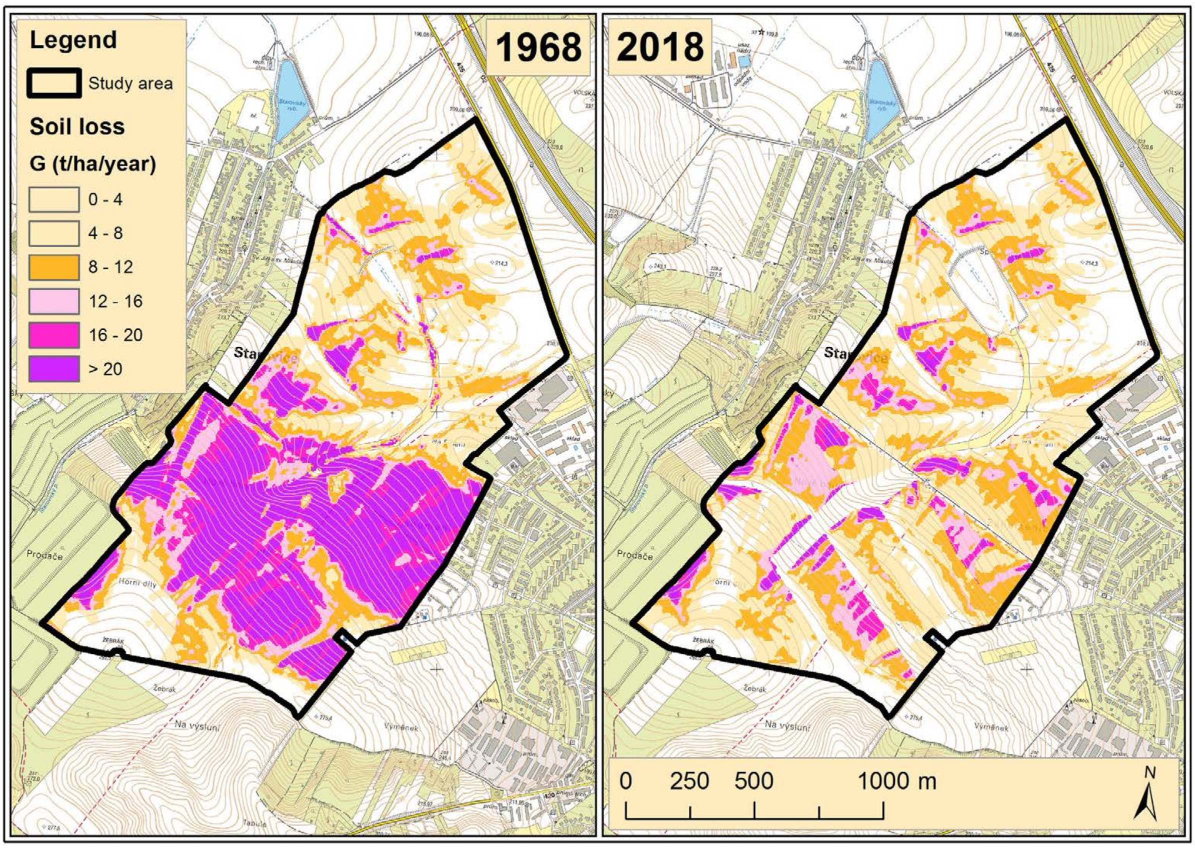

Fig. 6. Mean long-term soil loss by water erosion in the time periods 1968 and 2018 (USLE 2D model)

original horizon of arable land. The poles were installed around the year 1980. Due to the land tillage and subsequent erosion, the surrounding soil has been washed off (about 50 cm of arable land).

The results of the WaTEM-SEDEM model (see Fig. 9) showed a significant reduction of the transport of sediment from the study area. According to this model, in the time period 1968, erosion caused a mean loss of 278 t of arable land per year (11% of total erosion in the study area – the remaining 89% of the eroded sediment are accumulated at the bases of slopes). After implementation of anti-erosion and water-management measures, the total loss of sediment (arable land) decreased to 167 t of arable land per year. This represents a 40% reduction compared to the time period 1968. The application of protective measures has significantly reduced the soil loss by erosion and sediment transport out of the closing profile of the catchment.

The eroded volume of soil can be multiplied by the mean marketed price of arable land for financial assessment of the soil loss in the locality. The mean price of arable land in CR is about 350 CZK/t (14 €/t). This price does not include the qualitative characteristics of arable land, costs of clearing mud from reservoirs, transport, etc. The actual costs will therefore be significantly higher. Part of the eroded material remains accumulated at the bases of slopes. The costs for gathering, loading, transporting, and spreading the soil from the slope bases back to the land block amount to about 100 CZK/t (4 €/t) (Konečná, et al. 2013).

The price of arable land transported outside the study area (total sediment export) in the period 1968 reached around 3,892 €/year and in 2018 about 2,338 €/year. The effects of the adopted measures reduced the loss of arable land and sediment transport out of the study area by 111 t, which roughly corresponds to 1,554 €/year. How-

Fig. 7. Documentation of erosive processes in the study area

Table 2. Assessment of the soil loss by water erosion in the time periods 1968 and 2018

Soil loss by erosion [t/ha/year]	1968		2018	
	[ha]	[%]	[ha]	[%]
0 – 4	43.6	19.5	66.9	29.9
4 – 8	49.1	22.0	78.1	34.9
8 – 12	33.5	15.0	45.3	20.3
12 – 16	22.5	10.1	19.8	8.9
16 – 20	20.5	9.2	7.8	3.5
> 20	54.3	24.3	5.6	2.5
Area [ha]	223.5	100.0	223.5	100.0
G_{mean} [t/ha/year]	16.5		7.2	

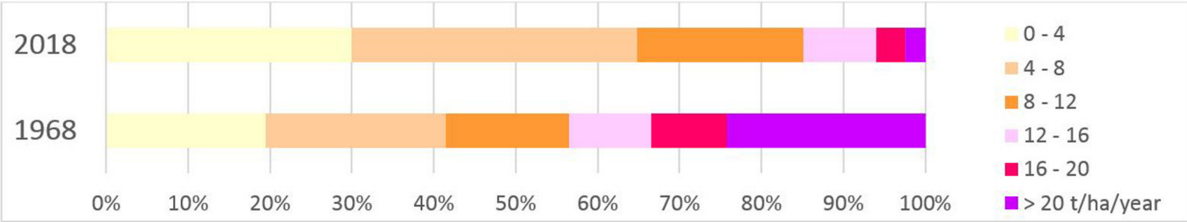

Fig. 8. Percentage of the mean long-term soil loss in t/ha/year in the time periods 1968 and 2018

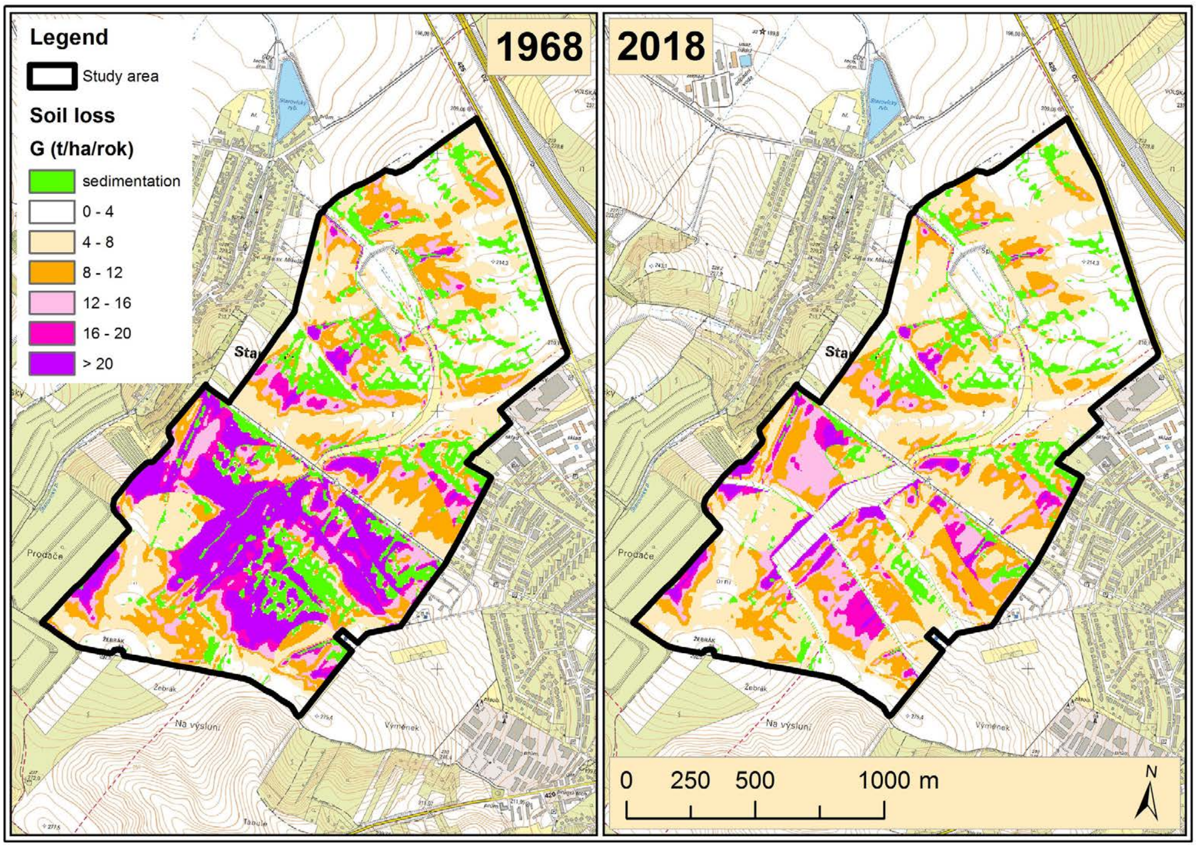

Fig. 9. Localization of surfaces at risk of erosion with sites of potential sediment accumulation (WaTEM-SEDEM model)

ever, large amounts of arable land were washed out by erosion from the upper parts of slopes to accumulation zones. The arable land thus remained in the area, but was exported to other locations. In such case, we have to include the costs for its relocation. In the period 1968, the volume of accumulated washed-off arable land was around 2,228 t/year. In the period of 2018, this value decreased to 1,365 t/year. The reduction by 863 t corresponds to a rough reduction of costs for relocation of this arable land by 3,452 €/year.

In total, the potential costs (loss of arable land, potential costs of its relocation) in the period 1968 may be around 12,804 €/year. In the period 2018, these costs were decreased to 7,798 €/year. Thus, the annual savings amount to about 5,006 €.

CONCLUSIONS

Erosive processes have accelerated in South Moravia (Czech Republic), particularly in the second half of the 20th century. Due to collectivization of agricultural land, large blocks of arable land were created. Unfortunately, this situation persisted even after the change of the political system in the 1990s. The case study performed at the borderline between two cadastral areas, Hustopeče near Brno and Starovice, confirms these facts. The study area situated at the borderline between cadastral areas Starovice – Hustopeče near Brno, with a surface area of 223.5 ha, represents a typical example of the South Moravian landscape. Our study analysed the land use and landscape

Table 3. Results of the WaTEM-SEDEM model – erosion and transport of sediment

Soil loss	1968	2018	Difference	Decrease
	[t]	[t]	[t]	[%]
Total sediment production	2506	1532	974	38.9
Total sediment deposition	2228	1365	863	38.7
Total sediment export	278	167	111	39.9

Table 4. Economic balance of the soil loss in the study area

Time period	Total sediment deposition			Total sediment export			Total	
	[t] / year	€ / t	€ / year	[t] / year	€ / t	€ / year	€ / year	€ / 10 years
1968	2228	4	8912	278	14	3892	12804	128040
2018	1365	4	5460	167	14	2338	7798	77980

structure in temporal series starting from the first half of the 19th century to the present. The analysis shows the changes in the modes of agricultural production – from farming at small fields (about 548 land blocks in the study area in 1825) of a mean size ca 0.5 ha to the creation of a single large block of arable land covering the entire study area. The worst situation was recorded, according to the available map documents and historical aerial images, starting from the period 1968. For this temporal series, we evaluated the risk of water erosion. The mean long-term soil loss by erosion amounted to around 16.5 t/ha/year. Parts of the land block with extreme values of soil loss about 50 t/ha/year were no exception. The trend of unsparing management of arable land lasted until 2003. At that time, the locality was proposed for land consolidation. Its main goal was to protect the built-in area of the municipalities against floods and manage extreme erosion at agricultural land. The proposal included grassed thalwegs, diverting contour furrows, retention grass belts, and dry retention reservoir. These measures were aimed at reducing the erosion risk, supporting infiltration of rainfall water, and decelerating the surface runoff. The application of these measures started in 2007 and was completed in 2017. At present, the study area contains a system of functional protective measures. The mean long-term soil loss by erosion was reduced to the values reaching around 7.2 t/ha/year, i.e., less than a half compared to the state in 1968. During the erosive processes, part of the sediment remains accumulated in the locality and part is washed off to water courses and reservoirs. Using the WaTEM-SEDEM model, we found that the application of the protective measures reduced the total soil loss by erosion in the study area by 40% (111 t/year). The economic balance showed a positive effect of the adopted protective measures. This evaluation was based on the mean price of arable land in the Czech Republic and the mean costs for relocation of arable land within the study area. The application of the protective measures thus brought an economy of at least 5000 € per year (22.4 €/ha/year). However, this sum does not reflect a potential decrease of agricultural crop yields due to the soil degradation, reduction of ecosystem services, and other factors. The actual benefits of applying the protective measures aimed at reducing erosion and increasing water retention in the landscape are significantly higher.

Acknowledgements

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