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Landscape changes as a factor affecting the course and consequences of extreme floods in the Otava river basin, Czech Republic

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Abstract The paper presents the analysis of anthropogenical modifications of the landscape in relation to the course and consequences of floods. The research was conducted in the Otava river basin which represents the core zone of the extreme flood in August 2002 in Central Europe. The analysis was focused on the key indicators of landscape modification potentially affecting the runoff process – the long-term changes of land-use, changes of land cover structure, land drainage, historical shortening of the river network and the modifications of streams and floodplains. The information on intensity and spatial distribution of modifications was derived from different data sources – historical maps, available GIS data, remote sensing and field mapping. The results revealed a high level of spatial diversity of anthropogenical modifications in different parts of the river basin. The intensive modifications in most of indicators were concentrated in the lowland region of the river basin due to its agricultural use; however important changes were also recorded in the headwater region of the basin. The high spatial diversity of the modifications may result in their varying effect on the course and consequences of floods in different parts of the river basin. This effect is demonstrated by the cluster analysis based on the matrix of indicators of stream and floodplain modification, physiogeographical characteristics and geomorphological evidences of the flood in August 2002, derived from the individual thematic layers using GIS.

Keywords Floods · Hydrology · Landscape · Land-use changes · GIS

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Introduction and objectives

Floods, extreme manifestations of precipitation and runoff processes, form an integral part of the environment and actively participate in landscape formation. After the devastating floods in Central Europe in 1997 and in 2002, we cannot help but question the extent to which the course and consequences of these floods were influenced by anthropogenic environmental changes. Other important questions include whether and where such floods might repeat, and how to ensure effective flood control. We are likely to see further climatic changes affecting the local area by extreme weather conditions, i.e. a higher incidence of floods (Baena et al. 2006; CHMI 2003; Vaishar et al. 2000; Vilímek et al. 2003; United Nations 2005). To come up with an objective solution, it is vital to identify key anthropogenic factors influencing the precipitation–runoff process, to quantify the scope of environmental changes caused by human activities, and to assess their impact on extreme hydrological situations like floods.

The effect of environmental changes, namely the impact of land-use change on the runoff process, is a subject of multiple research projects in various geographical conditions. Many of the studies are focused on the role of forest cover or the complex changes of the land cover matrix apparent from satellite imagery of available geodatabases (Brath et al. 2006a, b; Crooks and Davies 2001; De Roo et al. 2001; Fohrer et al. 2001; Tu et al. 2005). Other aspects of landscape changes that are affecting the runoff process during flood events, like land drainage or river network modifications, are assessed less frequently due to the general lack of information on the landscape transformation, in hand with difficult application of these data in current models (e.g. Dolezal et al. 2001; Stover and Montgomery 2001; Wiskow and van der Ploeg 2003).

The aim of this paper is to analyze the links between the various aspects of changes in landscape and the course and consequences of the catastrophic flood in August 2002 on the example of the core area of the flood – the Otava river basin. Individual aspects of landscape modifications were analyzed from historical maps, current map sources, digital elevation model (DEM), and satellite imagery. The information was completed by the field mapping of stream modifications and of geomorphological evidences of the flood. The cluster analysis was carried out to determine the interrelations among individual aspects of landscape modifications, physiogeographical features of the river basin and the flood course and its consequences.

Material and methods

Applied methodology

The applied methodology draws on application of comprehensive geographic analysis focused on individual environmental features. Integrating analytical aspects of the solution by GIS methods, it was possible to make a synthetic classification of the river basin in terms of flood consequences and their links to anthropogenic river modifications, anthropogenic transformation intensity, historical and current land use changes, and physical and geographic characteristics of the river basin (Vilímek et al. 2003; Langhammer 2003).

Principal analytical parts of the solution were focused on the following:

- Analysis of historical floods
- Analysis of the river network historical shortening
- Analysis of land use structure and historical changes
- Mapping and analysis of the river-bed and floodplain modifications
- Mapping of geomorphological effects of 2002 flood
- Analysis of floodplains land use and flood overflow

Individual factors affecting the runoff were analyzed using information from available data, historical records, topographical maps, remote sensed data, digital elevation models and field mapping. All data were integrated into the GIS geodatabase and consequently analyzed using geostatistical methods.

Data sources

The analysis of environmental changes was based on various data sources. The geodatabase ZABAGED, provided by the Czech Agency for Nature Conservation and Landscape Protection (AOPK CR), served as the main topographical material and this was completed by further thematic layers linked to analyzed landscape features.

The analysis of rainfall–runoff conditions draws on time series from monitoring stations of the Czech Hydrometeorological Institute (CHMI).

Long-term land use trends in the Elbe river basin were assessed using a geodatabase of long-term land use changes in CR land registers in 1845, 1948 and 1990, made by the Department of Social Geography and Regional Development of the Faculty of Science in Prague. It facilitates analysis of long-term land use alterations and identification of main quality trends in landscape development, and their spatial aspects.

Detailed development of land use, land cover, and quality aspects are assessed through a multi-temporal analysis of Landsat TM satellite images from 1987, 1996, and 2002. The CORINE land cover geodatabase of the Czech Ministry of Environment was used as a reference.

Shortening of the river network was analyzed using the historical military maps of the 2nd and 3rd mapping by the Austrian Empire in 1844 and 1869–1887, maps of the Czech Army Headquarters (GŠ CSA) from 1952, and the ZABAGED vector layer of water lines representing the current status.

The anthropogenic modifications of the river network and floodplain and the geomorphological evidences of the 2002 flood were assessed with help of the field mapping methodology developed at the Department of Physical Geography, Faculty of Science (Langhammer and Matoušková 2006).

The cluster analysis was used as a method to identify similarities among the individual aspects of river network modifications, physiogeographical features of the river basin and the observed evidence of the 2002 flood. There was applied the agglomerative hierarchical clustering algorithm (AHC) with the Pearson's correlation coefficient as a measure of similarity.

The clustering was based on the elementary elements of the floodplain – sections delineated in the course of field mapping. Seven hundred thirty-seven elements with an average length of 250 m were delineated. All information from individual analytical layers was integrated into these units using GIS. The input data matrix consisted of 22 parameters that are listed in Table 1.

Study area

The methods stated above were applied to the Otava river basin located in the southern Bohemia in the montane region at the border with Germany (Fig. 1). The study area represents a region with diverse physical and geographical features affected by varying intensity of anthropogenic pressure.

The southern part of the river basin is located in the top part of the Bohemian Forest (*Šumava mountains*) formed by leveled surfaces with an altitude over 1,000 m a.s.l. This area has prevailing natural character with scarce settlements and a forestation ratio exceeding 80%. The central part of the river basin is located in a hilly area with small settlements and extensive farming. The lowland area of the Otava and Blanice course is marked by the intensive agriculture, large settlement and intensive human activities as well as by the extensive artificial modifications of watercourses and floodplains.

The study area covers 2,982 km^2 with 520 km of watercourses of fourth and higher order, according the Strahler classification. The river system backbone is

Table 1 Input parameters for cluster analysis

Parameter	Unit	Data source
Mean altitude of the element	m.a.s.l.	DEM
Mean element slope	%	DEM
River route modifications	Category	Field mapping
Modifications of river-bed	Category	Field mapping
Modifications of stream longitudinal profile	Category	Field mapping
Modifications of floodplain	Category	Field mapping
Number of weirs in element	Number	Field mapping
Number of bridges in element	Number	Field mapping
Inadequately placed objects in riverbed or floodplain	Number	Field mapping
Number of rock steps in riverbed in element	Number	Field mapping
Share of urban areas in the element landcover	%	Corine landcover
Share of arable land in the element landcover	%	Corine landcover
Share of meadows in the element landcover	%	Corine landcover
Share of forests in the element landcover	%	Corine landcover
Share of total agricultural land in the element landcover	%	Corine landcover
Shortening of the stream in the element between 1844– 2002	%	Historical maps
Shortening of the stream in the element between 1876 – 2002	%	Historical maps
Shortening of the stream in the element between 1952 – 2002	%	Historical maps
Number of fluvial accumulations after the 2002 flood in the element	Number	Field mapping
Number of stream bank cavings in the element	Number	Field mapping
Number of destroyed bridges in the element	Number	Field mapping
Number of landslides in the element	Number	Field mapping

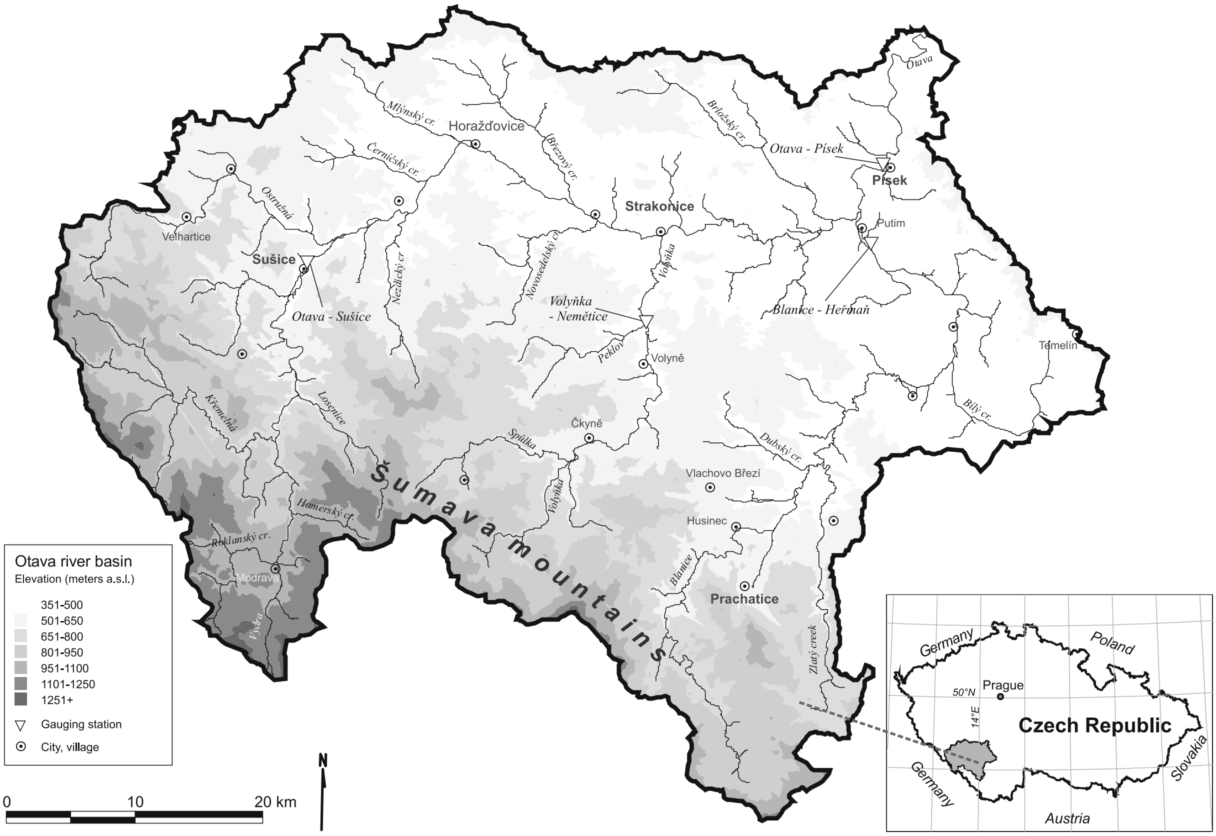


Fig. 1 Map of the study area – the Otava river basin and its localization in the Czech Republic

formed by the Otava, Blanice, and Volyňka rivers. For the purposes of the analysis, the river basin was divided into 16 sub-basins delimited by main gauging stations. Analyses and mapping covered 610 km of principal watercourses located in all parts of the river basin (Fig. 1).

Results

The course of the 2002 floods in the Otava River Basin

In August 2002, the Otava river basin was affected by two causative precipitation waves. The first wave hit the area on August 6–7, 2002 and the second on August 11–14, 2002. The overall precipitation volume in the basin was 0.737 km^3 (CHMI 2003).

The spatial precipitation distribution in the basin was rather asymmetric, reaching the highest volumes in the mountainous areas of the Blanice and Volyňka upstreams, the Hamerský Stream, and the Losenice. Here, the overall precipitation volume in the period from August 6 to August 15, 2002 exceeded 340 mm. The lowest precipitation rate was found in the Otava downstream area and on its left-side tributaries, reaching a total of 170 mm over the same duration.

Surprisingly low precipitation volumes in the otherwise extremely humid Vydra upstream area were caused by orographic effects of precipitation falling on windward slopes. This left the Šumava mountains in a rain shadow (Fig. 2). The precipitation height distribution is reflected in a map indicating the total volume of flood-driving precipitation in individual basins and partial volumes of both waves during the flood.

The flood course and consequences were negatively affected by two consecutive precipitation waves. The first wave led to a total saturation of the river basin making it unable to absorb the following stronger wave. The total precipitation volume of the whole period was highly determined by the second wave, reaching in

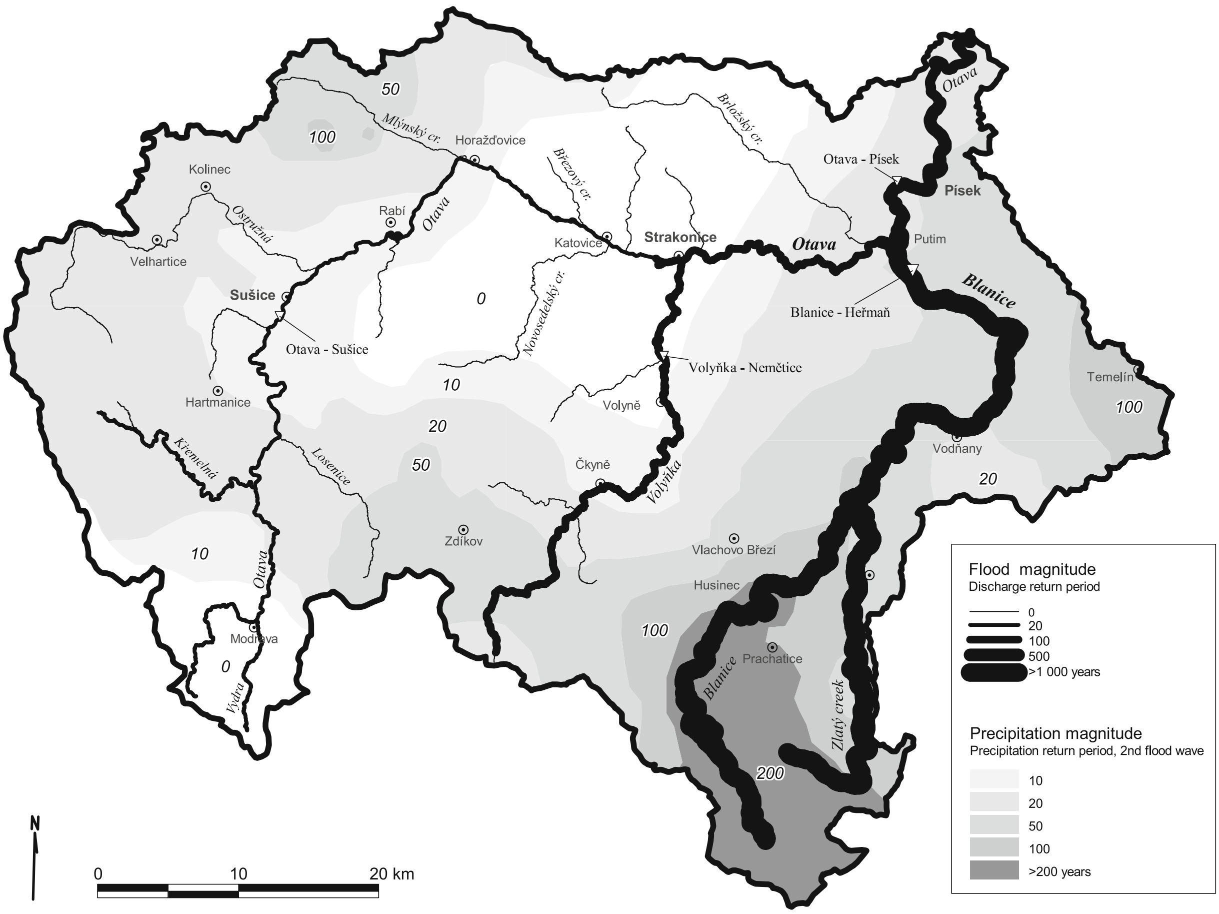


Fig. 2 Distribution of precipitation and extremity of runoff during the flood in August 2002 in the Otava River basin. Data: CHMI

average 52% of the total volume and locally representing 34–64% of the total. Its highest share was detected in the marginal parts of the river basin where flood waves are formed.

The runoff response in the Otava river basin during the August 2002 flooding reflects the spatial distribution of causal precipitation. The flood magnitude was highest in the headwater region in the montane area, especially in the Blanice river basin where the peak flows recurrence was higher than it has been in the past 1,000 years.

The runoff recurrence intervals were higher than precipitation recurrence intervals at the respective stations for both flood waves. During the second flood wave, the spatial concentration of precipitation and high saturation of the river basin from the preceding event resulted in extreme values of discharge recurrence intervals in Blanice (Table 2).

Flood wave hydrographs in the Otava selected profiles (Fig. 3) show that the location of causative precipitation in the core area had a significant effect on the subsequent fast flood development. Moreover, physical and geographic conditions in the river basin and its strong anthropogenic modifications didn't provide sufficient space for effective flood wave transformation or for any significant reduction of peak discharge values. Hydrographs clearly point to river basin saturation during the first flood wave and a steeper and faster character of the second wave that brought about considerably higher peak discharge values and flood magnitude under the same precipitation volume.

The flood had the most catastrophic consequences in the Blanice river basin where many residential buildings, bridges, infrastructures and regulation facilities were damaged or destroyed. On the contrary, the lowest damage was recorded on the upper and midstream

Table 2 Extremity of precipitation and runoff during the flood in August 2002 in selected stations in the Otava river basin (data: CHMI and Vltava River Basin Authority)

Flood in August 2002				1st flood wave				2nd flood wave			
River	Station	Precipitation (mm)	Runoff (mm)	API 11.8.2002 (mm)	Precipitation recurrence interval (years)	Peak discharge (m^3/s)	Discharge recurrence interval (years)	API 11.8.2002 (mm)	Precipitation recurrence interval (years)	Peak discharge (m^3/s)	Discharge recurrence interval (years)
Otava	Sušice	280.1	141.6	31.3	10–50	109	2	117.8	20–50	299	50–100
Otava	Písek	250.8	136.4	39.3	20–50	558	20–50	113.8	50–100	1180	500–1000
Volyňka	Nemětice	250.6	148.4	38.1	20–50	126	20–50	113.0	50	199	200
Blanice	Heřmaň	266.7	154.1	47.8	50	191	50–100	119.3	200	443	>1000

Otava, mainly on small mountainous streams. In the midstream and downstream area, the watercourse mostly filled whole floodplain zones and caused considerable damage. This applies mainly to the Blanice, Otava and Volyňka midstream and downstream areas with their major tributaries. The depth of the water in the affected floodplains increased up to several meters. The flood consequences were therefore strongly determined by the character and state of the land use of the floodplains.

Land use changes

Over the last 150 years, the land use structure has been significantly changed due to increased anthropogenic pressure on land use intensity. According to the analysis of land use historical changes, the most intensive alterations affected the Otava mid and downstream areas, the Blanice river basin, and Zlatý creek including the headstreams. The least altered areas are found in the central part of the river basin, mainly on the Volyňka, the Nezdický creek, and the Otava between Sušice and Horažd'ovice.

The main factor is the loss of meadows and pastures caused by their transformation into areas of intensive agricultural use. This trend is most intensive in mountainous areas and in the Blanice and Otava mid and downstream areas (Fig. 4). The scope of forests in the Otava basin has been relatively stable over the last 150 years, with slight losses in the Blanice and Otava downstream areas showing the lowest forest percentage of the whole river basin. On the other hand,

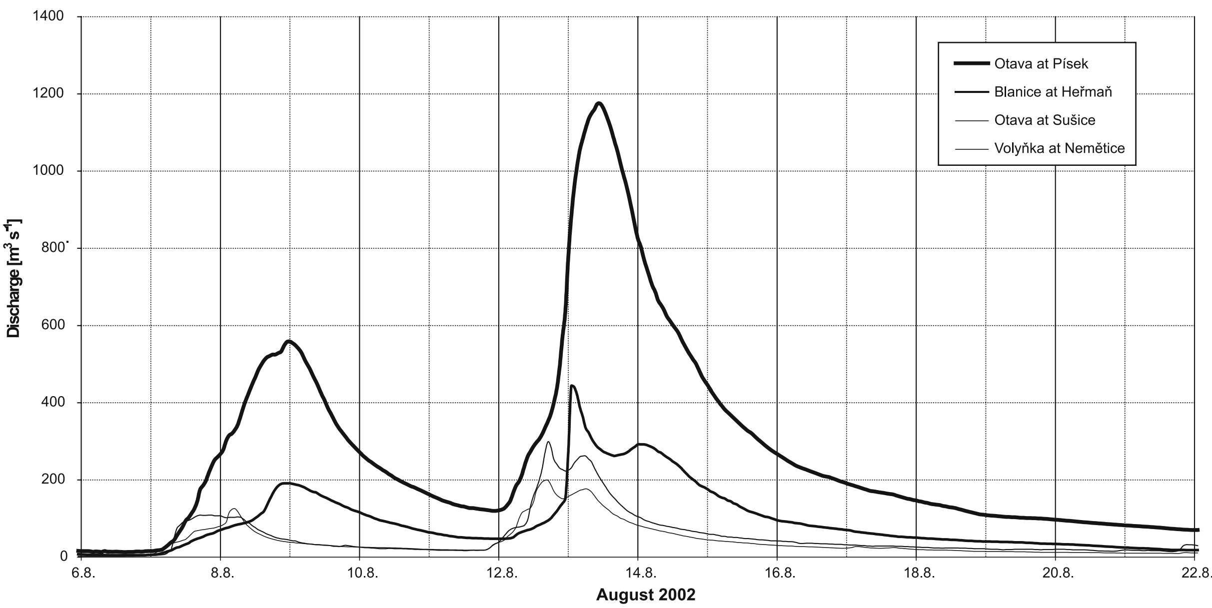


Fig. 3 Hydrographs of the flood in August in selected stations in the Otava river basin. Data: CHMI

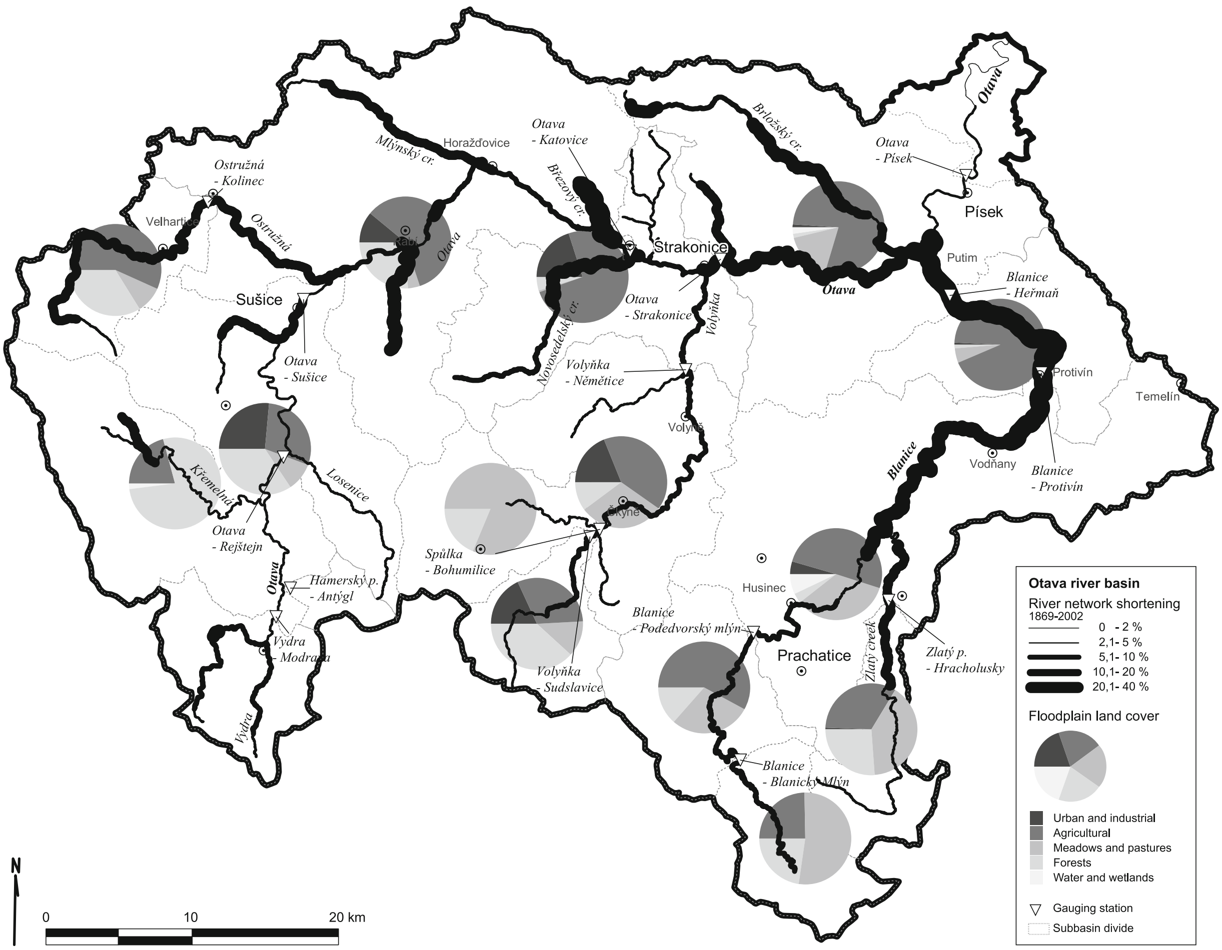


Fig. 4 Historical shortening of the river network and structure of land cover in floodplains in the Otava River basin. Data: Field mapping, Corine landcover

the mountainous areas show a slight increase in the forest share.

Over the last 20 years, dynamics of the land cover development has been quite low. We have analyzed Landsat TM satellite images and studied the land cover changes in the Otava river basin in 1987–1996–2002. The relatively small changes in the functional land use suggest that the river basin doesn't belong to dynamically developing regions. What is significant, in terms of runoff volumes and energy land balance, is the forest dieback in central Šumava caused by the bark beetle calamity in the mid 90s. This process has significantly influenced the river basin headstream area and the calamity extent is alarming. In the balance river basin delimited by the Vydra–Modrava station, forest dieback affected a total area of 12 km^2, i.e. 19% of the overall forest acreage.

Massive forest dieback in the headstream area significantly decreases the landscape retention capacity leading to considerable changes in the main hydrological balance parameters of the river basin. Decrease in the retention capacity plays an important role in the long-term perspective as well as on immediate responses to precipitation episodes, particularly under such extreme events as the 2002 flooding. Forest dieback in headstream areas speeds up the runoff wave formation making it steeper, due to lowered transformation capacity of the river basin, and faster in reaching downstream areas.

Another aspect of land use change in the assessed basin represents the agricultural drainage that was built here during the second half of twentieth century. The analysis based on digital water management maps proved that the subsurface drainage systems occur predominantly in the lowland downstream part of the river basin. The average share of the length of the subsurface drainage on the river network length is 9%, which corresponds to the average rates in the Czech Republic (Dolezal 2005). However there are substantial differences between the montane and lowland regions. In the headwater part of the basin located in the Šumava mountains, the drainage is scarce. However, in lowland agricultural areas of the Blanice and Otava rivers, the share of subsurface drains on the river length exceeds 20%.

Although the spatial extent of the subsurface drainage in some sub-basins is considerable it is quite difficult to assess the impact of the drainage network on the course and consequences of floods. The functionality of drains is highly varying mainly due to their chronically poor technical state. As the construction and maintenance of the drainage systems generally ended with the political changes after 1989, there is no data on their current technical state and functionality.

River network shortening

The analysis of the historical shortening of the river network has spanned the duration of the last 150 years. Analysis of spatial and temporal differences of stream lines on the maps of second and third military mapping (1844; 1869–1887), maps of the Czech Army Headquarters (GŠ ČSA; 1952–1957) and ZABAGED (2002) digital vector maps disclosed significant changes in the historical development of the river network in the river basin. Over the last 150 years, the total stream length has been reduced from 611.6 km to its current length of 555.9 km, i.e. by 9.1%.

Shortening occurred in all of the assessed phases and is evident even in the oldest supporting materials like the map of second military mapping, particularly in the midstream Otava area. The largest changes were introduced in the period marked by the issue of the map of the third military mapping and the maps of the Czech Army Headquarters (made at the beginning of the 1950s), when the Otava river lost a total of 6.6% of its length. The period of intensive modifications under the socialist economy that is usually blamed for the vast majority of landscape changes saw additional cuts of just 3% of the overall shortening, which is quite surprising. The Otava midstream and downstream river basin areas were intensively used from the middle of the nineteenth century. Floating of timber, transport of goods, and intensive agricultural activities significantly marked the face of the landscape, even before collectivization and agricultural industrialization introduced in the second half of the twentieth century.

The reductions differ quite significantly in individual parts of the river basin, reaching up to 40% of the original length in the Otava and Blanice downstream areas and their minor tributaries (Fig. 4). On the contrary, the upstream sections in mountainous areas weren't significantly affected due to the terrain morphology and smaller pressure on the land use. Watercourses in the Šumava central region, mainly the Blanice, Křemelná, Ostružná, and Vydra upstream areas weren't affected by modifications at all. Shortening of the Otava mid and downstream areas, where routes were already subject to modifications before the first monitored period, in average accounted for 10% of the original length.

Modifications of streams and floodplains

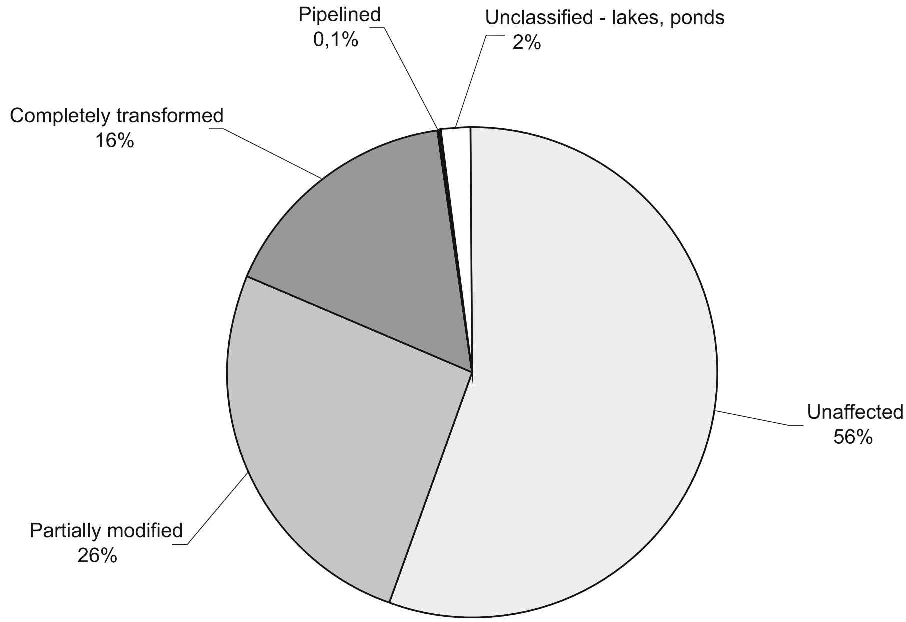
The current rate of the hydrographic network and floodplains anthropogenic modifications was determined by drawing on a field mapping of the 610 km long backbone of the Otava river basin. Assessment was conducted in five parameters of watercourse and riparian belt modifications:

- Modification of the watercourse route
- Modification of the longitudinal profile
- Modification of the river-bed
- Structure of the riparian belt land-use
- Identification of flood control measures and potential flood course obstacles

The field mapping and subsequent analysis results showed that the intensity of the overall anthropogenic modifications of the river network in the Otava river basin is remarkable. Currently, such anthropogenic alterations involve 43% of the total length, out of which 26% represent partial modifications, 16% represent complete modifications, and 0.1% is pipelined (Fig. 5).

The modification intensity significantly differs between regions. The largest extent of anthropogenic modifications is detected in downstream sections with intensive agricultural activities and dense population. Most intensive changes were identified in the downstream area of the Blanice river basin where the anthropogenically transformed stream segments are

Fig. 5 Structure of river network modification in the Otava river basin. Data: Field mapping, 2003



reaching almost 100% of the assessed river network length. Extensive modifications, however, also involve the Otava mid and downstream areas, the Ostružná and Spůlka basins, and the Volyňka and Blanice mid-stream areas. On the contrary, the river basin headstream areas (the Blanice and Vydra rivers) show only minimum modifications and the best conditions for natural water flow.

Water flow and flood consequences are also significantly affected by the inappropriate structure of anthropogenic modifications. Long and compact modified sections speed up the flow leading to concentration of erosion and accumulated material and intensive damage upon hitting unmodified zones, mainly in meanders and bends.

The highest attention should be paid to tube channeled sections that, despite their short total length, pose significant risks of considerable damage due to their blockage by material transported by flood waves. This leads to water accumulation and subsequent rupture, resulting in a significant increase of the flood wave's destructive capacity. Such problems arose on the Losenice river, where otherwise naturally formed river-bed was channeled into tubes in several places. The field mapping of flood consequences (Křížek and Engel 2003) indicated that these sections significantly intensified the 2002 flood damage in the respective river sections.

An important effect on the water flow during the flood had the weirs and dams. These regulatory structures that are altering the natural water flow are often centers of increased and concentrated flood consequences. Afflux above the dam causes overflow, accelerating sedimentation and leading to intensive erosion under weirs. Significant riverbank and weir damage is mostly incurred when such structures are situated in meanders or in a direction oblique towards the direction of the water flow.

Floodplains land use

The analysis of floodplain land use based on digital materials – satellite Landsat TM images from 1987, 1996 and 2002 and the CORINE land cover geodatabase – reveals inadequate land use structure in floodplains as well as in the overflow area of the 2002 inundation. Floodplains are dominated by arable land covering almost 43.8% of the total acreage. In total with the orchards and other types of farming, the agricultural land occupies 63.2% of the floodplain area. The meadows and pastures, the natural floodplain land cover, represent 15.9%, of the floodplain area, while forests and bushes represent 11.4%, and wetlands and water bodies represent 1.3%.

The floodplain land cover structure differs significantly between individual river basin areas (Fig. 4).

The highest shares of arable land occur in downstream areas that were heavily affected by the flood in August 2002. The Blanice and Otava floodplains show a share of all anthropogenically modified types of land cover exceeding 90% of the total floodplain area. However, a share of anthropogenically modified zones exceeding 50% is also detected in the mid and downstream areas of the Otava and Blanice river basins and in the Volyňka and Ostružná basins. The arable land here is also a considerable source of material for soil erosion, which results in subsequent sedimentation of high amounts of material in downstream areas.

Flood course obstacles

The analysis of geomorphological consequences of floods indicated that significant damage was mostly incurred in places of inadequate floodplain land use (Křížek et al. 2006). This concerns objects in the riverbed or floodplain changing the water flow direction, hindering water to spill into the floodplains the undersized bridges or culverts. In terms of the anthropogenic impact on flood consequences, this factor is undoubtedly the most critical and has to be considered in flood control policies.

Inadequately placed facilities most often involve railway or road embankments cutting through floodplains, acting as dams during floods and accumulating water. After reaching the critical moment, the weakest part (usually a bridge) is destroyed forming a flash flood wave spreading speedily down the river. Simultaneously, such areas are affected by high accumulation of material transported by the flood.

Inappropriately sized bridges or culverts have similar effects. They are blocked by transported material due to their low capacity, impeding further flow. Subsequent rupture of such artificial barriers leads to the destruction of the bridge or culvert and formation of a secondary flood wave causing extensive damage. This process could be illustrated by the events around the bridge on the upstream Blanice in the Otava river basin during the 2002 flood. Due to its location at the end of the valley and the low capacity, it was blocked by transported material forming a dam and accumulating enormous amounts of water that, after destroying the bridge, flooded another already full waterworks in Husinec, endangering its safety (Fig. 6).

Cluster analysis of flood consequences in relation to the landscape modifications

To synthetically evaluate all the analyzed parameters, watercourses were subject to a geostatistical classification sorting them into five clusters showing similar characteristics of historical and current river-bed and floodplain modifications, floodplains land use,

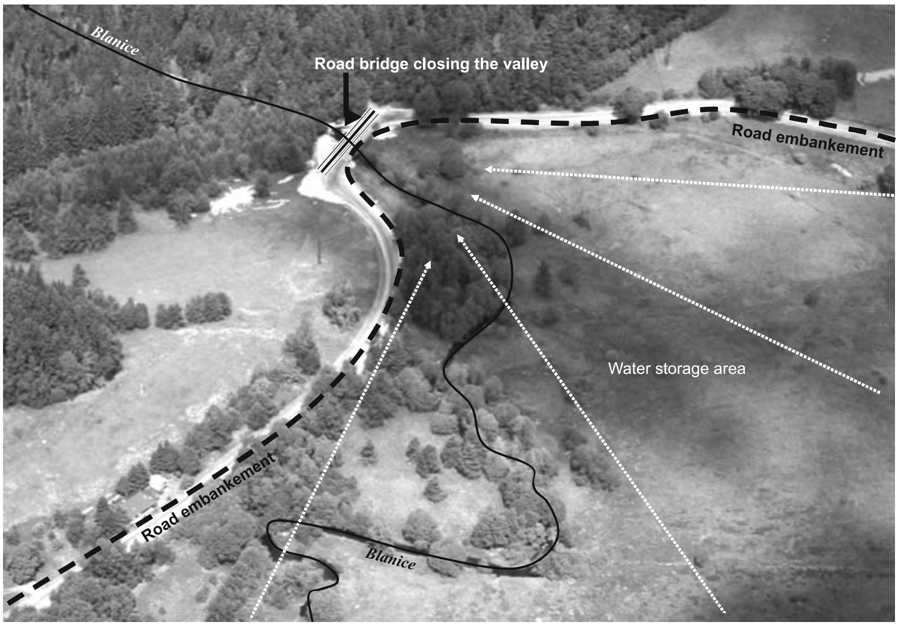


Fig. 6 Improperly located and insufficiently designed road bridge on the upstream Blanice River. Blockage and consequent collapse of the bridge in August 2002 endangered the Husinec Dam located 8 km downstream. Photo by Langhammer (2003)

flood evidences, and watercourse physiogeographical characteristics.

Classification resulted in four major groups of parameters completed by one independent parameter. The major groups are the physiogeographical features, riverbed modifications, stream shortening and geomorphological evidences of floods. Selected types of stream modifications correspond to the typical character of land-use. However, the occurrence and structure of geomorphological effects of floods are almost independent of the assessed parameters of landscape modifications (Fig. 7).

The *physiogeographical features* of elements – mean altitude and slope are closely linked with the share of forest in the floodplain elements that properly reflects the general geography of the basin.

Modifications of riverbeds are most closely linked to the urban space while they are differentiated into group of parameters describing the aspects of longitudinal profile modifications and modifications of the riverbed.

The *agricultural land use* of the floodplain area is linked with the severity of the river network shortening. This reflects the fact that the stream rectifications in the Otava river basin that were built during the last 150 years predominantly in the agricultural lowland regions to ameliorate conditions for farming.

The sole individual parameter of the floodplain that was not linked into any of the groups is the *potential flood course obstacles* represented by the insufficiently sized bridges, culverts or improperly placed objects in the riverbed or floodplain.

The occurrence of observed *flood effects* seems to be independent of any of the assessed parameters of stream, floodplain and basin modifications. This applies to the bank erosion, fluvial accumulation, as well as the traces of destruction in the assessed element.

Discussion

The research of the impact of environmental changes on flood risk points to complicated links between physiogeographical characteristics of river basins and their hydrographic networks, anthropogenic transformation, and responses to extreme runoff situations. However,

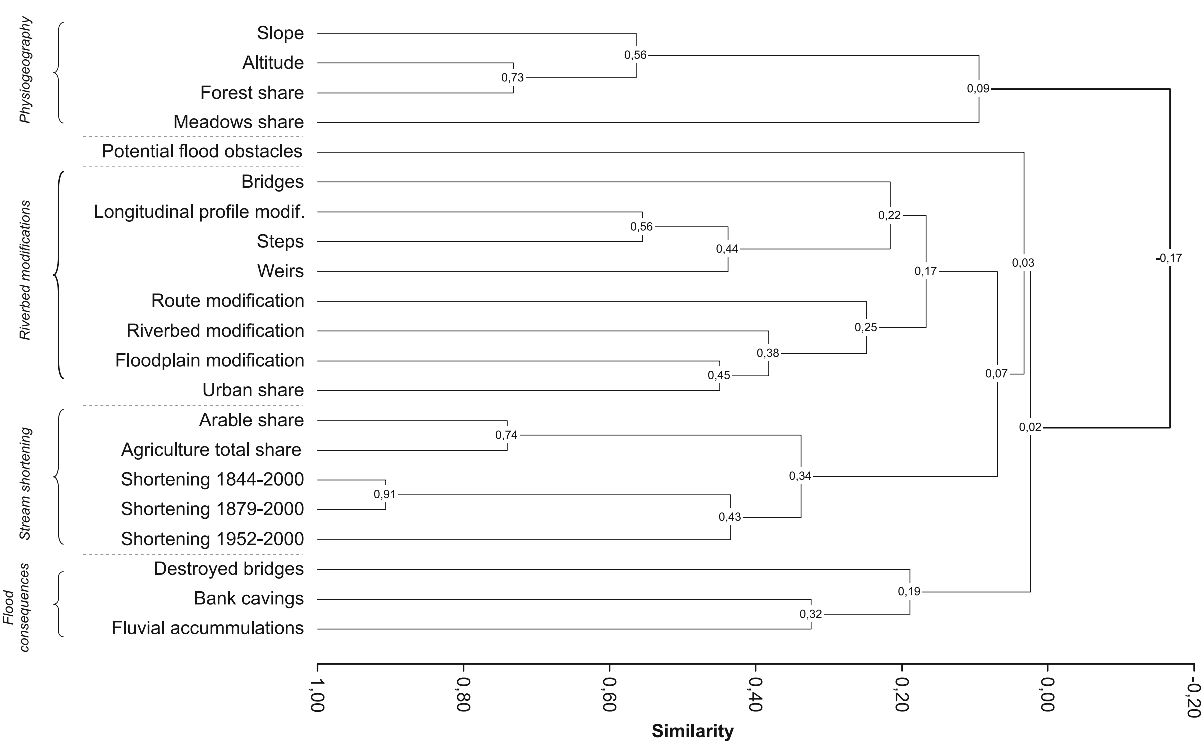


Fig. 7 Classification of river network according the stream modification, physico-geographical features and geomorphological evidences of the flood in August 2002 in the Otava River Basin. Data: Field mapping, 2003

the research in the Otava river basin hasn't proved that the current rate of the river-bed, floodplain and landscape modifications are directly linked with the extreme severity of the consequences of floods in August 2002.

The landscape and river network modifications have different effects on individual components of the runoff process during floods and negatively affect flood formation and consequences. Intensive landscape, floodplain and riverbed modifications lead to runoff acceleration, discharge intensification, steeper flood waves, changes in flood wave timing in individual river basins, and deterioration of landscape and floodplain transformational capacities.

These results are in line with current findings of studies proving that the direct impact of land use change on flood course and consequences is rather complicated and depends on other factors, namely on the spatial scale, flood magnitude and physiogeographical features of the basin (e.g. Cheng et al. 2002; Fohrer et al. 2001; Magilligan et al. 1998; Naef et al. 2002; Stover and Montgomery 2001; Robinson et al. 2003; Yang et al. 2000).

The individual landscape modification parameters and their groups derived by the cluster analysis in the Otava river basin thus should be assessed from the viewpoint of their potentially different impact under varying flood magnitude and on differences of the spatial scale of the analysis.

Factors of decreasing significance under growing flood magnitude

This category comprises the vast majority of assessed landscape modifications – changes in land use, stream and riverbed modifications or river network shortening. The impact of such factors is usually the highest in situations of floods with low severity when the river floodplain is not fully plugged into the runoff (Camorani et al. 2005; Maidment 1993; Hladný et al. 2005).

The critical threshold that marks a radical decrease in their impact differs locally and depends on the geographic characteristics of the river basin and the intensity and spatial distribution of causal precipitation. In the case of a flood of small magnitude, it is possible to affect the course of flood by the revitalization of streams and floodplains which result in an increase of the transformational effect and retention capacity of the floodplain and in a reduction of peak discharge values.

Factors of increasing significance under growing flood magnitude

This category of factors mainly comprises the potential obstacles to the flood situated in the riverbed or in the floodplain. Under floods of small and medium magnitude, such objects have very limited impact on flood consequences and on the resulting extent of the damage. However, once floodplains are fully inundated, the runoff process is also influenced by structures in floodplains that aren't usually hit by floods and have no flood control properties.

Results of field mapping of flood consequences in the Otava river basin (e.g. Křížek and Engel 2003) proved that the flood course obstacles caused the most intensive erosion and accumulation forms observed in the river basin.

Moreover, buildings and facilities in the floodplains become sources of material transported by floods and accumulated in suitable locations. Such effects are mostly brought about by railway or road embankments cutting through floodplains and undersized bridges and culverts that were once blocked by transported material and thus accumulated large amounts of water. Final destruction of such temporary barriers leads to formation of secondary flood waves causing more extensive damage than under normal conditions.

Effect of spatial scale

In assessing the impact of landscape anthropogenic modifications on flood consequences, the applied spatial scale plays an important role (Niehoff et al. 2002). The effects of landscape, floodplains and river-bed anthropogenic modifications on flood consequences are the highest on a local level in small and relatively homogeneous tributaries of a limited acreage reaching

Table 3 Land-use structure of the floodplain (data: Corine landcover)

Land use category	Percent
Urban and industrial areas	8.2
Arable land	43.8
Other agricultural land	19.4
Meadows and pastures	15.9
Forests and bushes	11.4
Water and wetlands	1.3
Total	100.0

only several squared kilometers. Here, landscape and land use changes are most visible with respect to the rest of the river basin and have the strongest impact on the runoff process and landscape retention capacities (Baker and Costa 1987; Maidment 1993; Shi et al. 2007).

In large heterogeneous river basins, the impact of landscape modifications on the flood development and consequences is significantly lower as it is scaled down by the diversity of factors affecting flood formation.

In complex river basins on a regional and superior level, it is difficult to precisely quantify the effect of anthropogenic modifications or their share in the final flood extremity.

Conclusion

The presented research bring new information on the role of anthropogenic modifications of the Otava river basin during the catastrophic flood in August 2002 based on detailed field mapping and geostatistical analysis.

The results indicate that shortening of river courses, riverbed modifications and systematic drainage of agricultural areas have only limited impact on flood consequences. This is especially true in cases of floods with extreme magnitude and regional scale.

On the other hand, land-use structure of the floodplain and structures impeding free water flow represent a significant factor, which gains increasing importance with increasing flood extremity (Table 3). Facilities located in floodplain areas, e.g. railway embankments or undersized bridges or culverts often significantly worsen flood consequences due to artificial accumulation of water and occurrence of subsequent flash flood after the collapse of the blockage. Such critical elements were located in the upper part of the river basin where they affected the forming flood wave as well as in the lowland agricultural regions where they were followed by important geomorphological effects. It is also important to point to the negative impact of intensive agricultural use of floodplains in lowland areas impeding effective retention and flood wave transformation.

Cluster analysis based on different parameters of the river network, floodplain and landscape modifications, physiogeographical features and flood consequences proved that the geomorphological effects of the flood in August 2002 are not directly related to any kind of river network and floodplain modifications. At the same time it demonstrated that the different forms of stream modifications are linked with the prevailing character of land use except the potential flood course obstacles which occurs irregularly in the whole river network.

The results also indicate the potential and limits of flood protection measures based on stream revitalization and changes in land use of the floodplain area.

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