

## GEOMORPHIC RESPONSE TO THE LITTLE ICE AGE IN SLOVAKIA

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**Abstract:** Geomorphic response to the Little Ice Age (LIA; ca 1250-1890 AD) in Slovakia was marked by the increased occurrence and effectiveness of fluvial, runoff, and some gravitational processes. We identified four periods of increased frequency of big floods, namely: (1250) 1378-1526 AD, the 1560s-1570s, the 1590s-1620s, and the 1660s-1850s, while the last period shows two stages (the 1660s-1720s and the 1760s-1850s). Three identified periods of disastrous gullyng accompanied by muddy floods (the 14<sup>th</sup> century, the mid-16<sup>th</sup> century - the 1730s, the 1780s - the mid-19<sup>th</sup> century) refer to temporal conformity of both fluvial and runoff processes. High frequency of debris flows in the Slovak part of the Tatra Mts. occurred in the period of 1400-1860 AD. Sparse mentions on precipitation-induced particular events of debris flows, landslides or rockfalls are mostly linked with simultaneous occurrence of floods.

**Key words:** geomorphic response, floods, gullyng, muddy floods, debris flows, landslides, rockfalls, Little Ice Age, Slovakia

### INTRODUCTION

Four periods of accelerated runoff geomorphic processes (water soil erosion) occurred in the territory of the present-day Slovakia in the past. The first one was linked with the Late Bronze Age (1250-750 BC), the second one with the Great Moravian Empire (mostly with the 9<sup>th</sup> century), and the third period with the so-called Great Colonization in the 13<sup>th</sup> and 14<sup>th</sup> centuries when the settlement penetrated more massively also to the Carpathians (Bučko, 1980; Stehlík, 1981). Historically, the fourth period overlaps temporarily with the development of the dispersed settlement, which originated as a product of the youngest colonization waves, namely the Wallachian, „kopanitse“ and Goral, in the 16<sup>th</sup> through 19<sup>th</sup> centuries (Stankoviansky, 1998). All these erosion cycles resulted from cumulative, multiplied effect of synchro-

nously operating anthropogenic and climatic influences.

However, if colder and wetter climatic fluctuations in the past contributed to the acceleration of runoff processes, they had to contribute equally to the increased activity of the other precipitation-induced geomorphic processes, namely floods and muddy floods, and also landslides, earth and debris flows and maybe even rockfalls. Unfortunately, though some works were dealing with historical aspects of the activity of such processes in Slovakia (concerning mainly floods), until recently minimum attention has been dedicated to the linkage between occurrence and geomorphic effects of these processes and climatic fluctuations. Only in the late 1990s and in 2000s, the works assessing increased occurrence and geomorphic effectiveness of some precipitation-induced processes connected with the last of

a series of historical climatic changes that affected the territory of Slovakia, namely LIA, did start to appear. Increased activity of floods within this period was indicated by P. Pišút, that of gullying and muddy floods by M. Stankoviansky, and that of debris flows by A. Kotarba.

The objective of this paper is to assess the character of geomorphic response in Slovakia to the LIA. It summarizes present outputs and presents new results concerning the timing, geomorphic effect and environmental impact of fluvial, runoff and some gravitational processes. Moreover, it tries to identify common phases of acceleration of these processes within the LIA.

#### **BRIEF OUTLINE OF PHYSICAL CONDITIONS AND LAND COVER IN SLOVAKIA**

The territory of Slovakia (49,035 km<sup>2</sup>) is of predominantly mountainous character. Its northern and central parts belong to the Carpathians (74% of the Slovak area) and its south-western and south-eastern parts to the Pannonian Basin. The Carpathians represent an arc-like mountain system elongated in a west-east direction, being divided into the Outer and Inner Western/Eastern Carpathians. The extensive Pannonian Basin penetrates into the Slovak territory in the form of three separated sub-Carpathian lowlands.

The geological structure of the Slovak territory is very heterogenous. The Outer Carpathians are built by complexes of the Flysch and Klippen belts. The northern part of the Inner Carpathians consists mainly of the so-called core mountains built up of crystalline rocks and cover sedimentary complexes (consisting mostly of limestones and dolomites). The southern part of the Inner Carpathians is built of volcanic rocks. The above rock complexes differ significantly in their resistance, resulting in changing thicknesses of the regolith. Predominant part of the intra-Carpathian basins and all sub-Carpathian lowlands

is underlain by the Neogene strata of low resistance. However, they are almost completely covered by thick layers of Quaternary deposits, mostly fluvial sandy gravels, loess and blown sands.

Most of the Slovak territory is a part of the Danube River basin and is drained to the Black Sea. Only smaller part of northern Slovakia with the Poprad and Dunajec rivers does belong to the Baltic Sea catchment. Slovakia is a source area and majority of its streams are fed by rainfall. Only the rivers Danube and Morava do bring water from abroad. As to the hydrological regime, the typical major Slovak rivers, such as Váh, Hron, Nitra, and Hornád, collecting waters mainly from mid-altitude areas, have maximum discharge in March/April. The eastern-Slovakian streams in flysch catchments have mostly uneven discharge and are prone to flash floods induced by torrential rainfalls. In general, fluvial erosion, transport, and river landform dynamics in Slovakia are most intense during the high-flow or summer time flood events, since about 40% of the yearly rainfall comes in summer (June to August).

From the viewpoint of spatial distribution of recent geomorphic processes in relation to the geological substratum and relief, but above all to vertical zonation of climate and vegetation, two morphoclimatic zones (systems) are distinguished in the territory of Slovakia in accordance with Kotarba and Starkel (1972). These are the temperate forest system and the cryonival system, separated by the upper timberline.

The rates of precipitation-induced geomorphic processes and, in the case of most of them, also their spatial organization are significantly influenced by land cover. The main land cover types in the current landscape of Slovakia are represented by agricultural land (45%, including 34% of arable land), occurring predominantly in the sub-Carpathian lowlands and intra-Carpathian basins, and by forests (38%), distributed mostly in mountains (Feranec and Oťaheľ, 2001).

## KNOWLEDGE OF THE LITTLE ICE WITH SPECIAL REFERENCE TO SLOVAKIA

According to Starkel (2000), of all climatic fluctuations, they are the wetter and at the same time colder periods typical of increased concentration of extreme meteorological-hydrological events, both rainfall and snowmelt, that exhibit a significant geomorphic effect. The only important representative of such a period within the last millennium is the Little Ice Age (LIA). The LIA took place, according to Lamb (1984), in the period of 1550-1850 AD or, according to Flohn (1982), in the period of 1570-1860 AD. Later discussion located the beginning of the LIA back to the period shortly after 1300 AD (Pfister et al., 1996, 1998) or even to 1250 AD (Porter, 1986). There was no similar debate about identification of the end of the LIA; according to different authors its dating ranges between 1850 and 1890 AD (cf. Brázdil, 1996). In the sense of this discussion, we can understand the time span of the LIA in Slovakia *sensu stricto* (according to Lamb, 1984) and *sensu lato* (according to Porter, 1986). In the case of the broader understood LIA, it followed directly after the Mediaeval Warm Epoch (MWE), without „the Transitional period of climate deterioration“, delimited as an independent unit before (cf. Brázdil, 2000). This paper deals with the geomorphic response of the LIA *sensu lato*. However, the time span of the LIA in the highest parts of the Slovak Carpathians – the Tatra Mts., was related to the 1400-1925 AD period (Kotarba, 2004).

Unfortunately, our knowledge of the succession of wetter (colder) and drier (warmer) fluctuations in the pre-instrumental period is rather poor, as the reconstruction of climate in Slovakia is very recent and even not made by Slovak climatologists (Brázdil and Kiss, 2001; Brázdil et al., 2008; Büntgen et al., 2009). Large number of data on various hydroclimatological events from the Slovak part of the historical Hungary was collected by Réthly (1962, 1970).

The period of daily weather observations at the Košice Jesuit friary in 1677–1681, as-

essed by Brázdil and Kiss (2001), was too short to be able to identify clusters of wetter and colder years. Records from the first meteorological measurements in Prešov and Kežmarok (belonging to the Breslau /Wrocław/ meteorological network of the physician Johann Kanold) in 1717–1730 enabled to recognize 1725 as the extreme rainy and cool year with disastrous floods on Poprad, Váh, Smrečianka and Orava rivers (Brázdil et al., 2008). Tree ring data from pine trees in the Popradská kotlina Basin made it possible to identify the wettest and driest years within the 1744–2006 period. The wettest period occurred just at its beginning, namely in 1745–1775, with 7 wet years. To the LIA period belong also wet spells in 1814, 1840, 1871, and 1876 (Büntgen et al., 2009).

The sparse data from Slovakia resulted in the dependence of the Slovak scientists in using the data on the evolution of climate in neighbouring countries with special regard to Czechia. To the knowledge on the climate development, at least in the westernmost part of Slovakia, can help a compilation and analysis of meteorological records dating back to 1803 from Brno, Central Moravia, and tree-ring width measurements from living and historical firs from southern Moravia dating back to AD 1500, performed by Büntgen et al. (2010). The identified wet years were as follows: 1505, 1530, 1574, 1579, 1649, 1675, 1712–1714, 1730, 1765, 1769–1772, 1796, and 1879–1880.

## MATERIAL AND METHODS

As to the historical floods, the present knowledge is mainly based on some chronicles, epigraphic sources (flood marks), mentions of floods in personal correspondence, diaries and even depictions of some flood disasters. The largest channel changes in the mediaeval period may be inferred from small-scale maps. Probably, the most important data on floods published so far, extending as early as the 15<sup>th</sup> century, are related to the Danube River. The most detailed records on floods and high waters relate to damage,

repairs and upkeep of several local bridges across the Danube channels in Bratislava and its surroundings, hausting water from bridge boats and diverting the drifted logs from the side channel into the main channel in order to protect the bridge construction (Király, 1890). Other data may be inferred from records on moving ice and damage to wooden fish weirs (for example in 1551 and 1581), constructed on the Lesser Danube and Lower Váh River for fishing of beluga (*Huso huso*) and other large sturgeons (Alapy, 1933). Since the 16<sup>th</sup> century, flood events have been documented quite well in the registers from county and municipal sessions. Since 1770s, information on floods has also been well documented by local newspapers (e.g., *Pressburger Zeitung*), early scientific works and numerous cartographic evidence, documenting their devastating effects. A really significant source with a large number of collected data on floods from the territory of historical Hungary is represented by publications of Réthly (1962, 1970), as many of them are related to the territory of the present-day Slovakia.

Geomorphic effects of historical gully erosion were assessed on the basis of an analysis of historical maps and written sources, field geomorphic investigation and detailed mapping at the scale of 1:10,000. The sets of maps of the 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> military mapping campaigns from the historical Hungary, coming from the 1760s–1780s, 1800s–1860s (both 1: 28,800), and 1870s–1880s (1: 25,000), respectively, indicated the spatial development of gully networks over time and their relative ages. The original written accounts by local priests helped in some cases in the relative dating of gully formation as well (cf. Stankoviansky, 2003a).

Unfortunately, nobody in Slovakia was dealing with the occurrence and effects of gravitational processes in the period of LIA. To complete information on geomorphic response to this climate change, we used the results of A. Kotarba who studied historical debris flows also in the Slovak part of the Tatra Mts. Rare mentions on landslides or rockfalls are based on sporadic historical records.

## RESULTS AND DISCUSSION

### FLUVIAL PROCESSES: FLOODS

There is no doubt that one of the most typical elements of the LIA climate with considerable impact on river morphology were severe winters, often with large amount of snow, during which even the lowland sections of major rivers in Slovakia used to be regularly frozen. Snow melting and/or the movement of ice on rivers often led to formation of ice barriers, causing major ice-jam floods. However, even “an ordinary” freezing of rivers and local ice movement could have led to significant geomorphic effects and heavy lateral erosion within a time span of days (cf. Pišút, 2008). Anyway, appearance of ice floods in general is much dependent on the course of ice movement and melting, on local morphology of river channels, and in some cases it could be also even happily prevented by direct human interference. This explains why some ice floods of regional or supra-regional scope did not result in similar disasters in certain Slovak rivers (e.g., in 1784 or 1838 on the Danube River). The most catastrophic ice floods in the Slovak reach of the Danube River occurred in the period between 1526 and 1850. Repeated winter-type floods were particularly common in the period between the 1760s and the 1850s. In general, occurrence of cold winters and ice floods in Slovakia seem to be in a quite good accord with data on severe winters throughout Europe (Brázdil and Kotyza, 1997; Koslowski and Glaser, 1999).

Nevertheless, the largest and most catastrophic hydro-climatic events of the LIA period on Slovak rivers with major geomorphic effects occurred in the summer months (July, August). Such disastrous inundations typically occurred after continuous, several successive days lasting heavy rainfall (in orders of tens of hours; cf. Brázdil et al., 2004) in some larger regions (Alps, Carpathians). These floods (e.g., 1501, 1662, 1725, 1787, 1813 events) are also relatively best documented by historical records.

Out of the 7 largest summer type floods in the Danube River with reconstructed

peak discharge over  $10,870 \text{ m}^3 \text{ s}^{-1}$  (at Bratislava), recorded since 1000 AD, five occurred within the period of 1500-1800 AD. Preliminary comparisons show a good accordance with data on floods from other Central European rivers (Brázdil et al., 1999; Munzar et al., 2005), and particularly with the tributaries of the Danube itself (Rohr, 2006).

Especially typical for the LIA period were also successions of several floods during one year, or even within a season (= several consecutive flood waves). Such clusters can promote the most pronounced geomorphic effects (Starkel, 2003). Several such periods are recognizable in Slovakia, which were also associated with the largest and most conspicuous changes in river behaviour.

PERIOD OF (1250)1378-1526 AD

According to Brázdil et al. (2005 and references therein), the hydroclimatic regime of the 14th century was probably already affected by the first spell of the LIA climate. Between 1378 and 1526 AD, a serious change of the river network occurred along the Slovak section of the Danube River, as indicated by cartographic, toponymic and other documentary evidence (Pišút, 2006). Due to large avulsions, which also affected the char-

acter and discharge of the Lower Váh River, the historical region of Vágköz between Komárno, Čičov, Topoľníky and Kolárovo became a part of the considerably enlarged Žitný ostrov Island, embraced between the Danube River and its anabranch called the Lesser Danube (Fig. 1). The most important avulsion produced a new course (16 km long) of the Lesser Danube between villages Topoľníky and Kolárovo (Pišút, 2006).

These changes were a result of repeated high flows and a number of major mediaeval floodings that affected large areas and basins of several Central European rivers, including the Danube itself (1012, 1210, 1316, 1342, 1432, etc.). Some of them consisted of clusters of two (1342) or even three floods (1432), probably with profound geomorphic effects (cf. Bork et al., 1998). Some shorter periods of increased lateral activity of the Danube River or major individual floods are also indicated by written evidence (late 1250s/early 1260s, 1300s or 1330s). However, there are several indices of special nature of the late mediaeval floodings. For example, a charter from 1393 reflected a sudden local channel change (probably chute cutoff) at the village Rusovce due to the Danube flood. A charter of the 1420s pointed out to dangerous lateral activity of

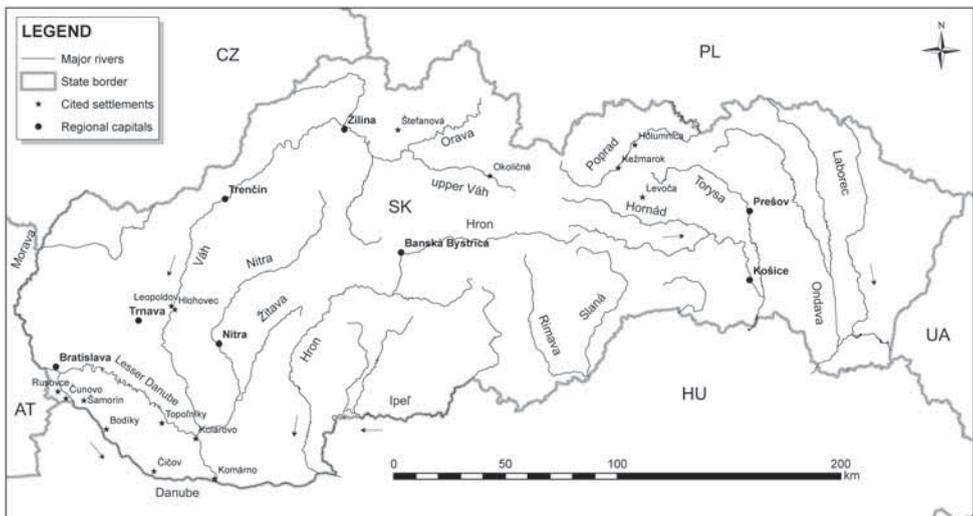


Figure 1. Location of main Slovak rivers and sites, mentioned in the subchapter on floods

the Danube's main channel near Šamorín town (Földes, 1896). According to another record, a series of floods at the lower Žitný ostrov Island made the agricultural activities impossible there for several consecutive years (Alapy, 1890).

In this period, besides floods due to snowmelt and ice (particularly in the 1420s–1440s with severe and snowy winters) and the extreme year 1432 with succession of three major floods (cf. Brázdil and Kotyza, 1997; Brázdil et al., 2004), the large summer-type floods occurred also in 1399, 1402, and from 1405 to 1408 (Tóry, 1952). One of the largest floods of the 15th century was that of 1489, again with three flood waves on the Danube (Réthly, 1962).

Major floods seems to have culminated in 1501–1526. The largest Danube flood of the past millenium (Rohr, 2006) occurred in August 1501, with the estimated discharge in Krems (Austria) of  $14,000 \text{ m}^3 \text{ s}^{-1}$  (Kresser, 1957; in Pekárová, 2010). In 1508, again at least two large flood waves occurred in July and August, although they did not reach the parameters of the 1501 flood. During the ice flood in 1516, the Danube penetrated into the inner town of Bratislava, taking a toll of human lives. The last disastrous flood of the mediaeval period occurred in Bratislava in 1526; since the ice barrier piled up overnight, the townsfolk were taken by surprise and 53 people drowned.

#### PERIOD OF THE 1560s-1570s

After a period of relatively warm seasons in the 1540s–1550s and reduced ice winter severity (cf. Koslowski and Glaser, 1999), the frequency and magnitude of large floods on the Danube increased again from 1560 AD onward, as did lateral activity of the river. A new stage of increased hydroclimatic activity is also well documented for several European rivers (Brázdil et al., 1999).

A significant cluster of repeated large floodings, both summer and winter-type floods, are documented in this period that stroke Bratislava and the downstream river stretch at Žitný ostrov Island in 1563 (June), 1565, 1566 (July), 1567, 1568, 1569, 1570,

1571, 1572 (July), 1573 (January, July), and in 1578. The flood of 1570 seriously damaged the imperial anti-Ottoman fortress in Komárno, built in 1546–1557. High flow around July 15, 1573 pulled down the bridge at Bratislava. This cluster of large floods included two (1572, 1578) out of the total of 7 historical floods, recorded at the Austrian Danube stretch since 1000 AD, that overtopped a peak discharge of 1899 major flood (over  $10,870 \text{ m}^3 \text{ s}^{-1}$  in Bratislava; Fekete and Láng, 1967).

Geomorphic effects of these floods are evidenced by a local meander cut-offs and by a dispute between the local landlords and the Bratislava municipality in 1588–1596, concerning the new alluvial territories around the Lesser Danube at the territory of the present-day Bratislava (Pišút, 2004). In reaction to extreme floods of this period also a first legislation was adapted, which ordered repair of old embankments along the Danube River and the construction of new ones (Fűry, 1998).

#### PERIOD OF THE 1590s-1620s

Another quite prominent cluster of major floods seems to have occurred in the 1590s and the 1610s–1620s. Besides the Danube River floodings, this phase is already also documented by extreme flood events in basins of major Carpathian rivers – Váh and Hron.

During the large floodings around the whole of central Europe in July 1593 (Brázdil et al., 2005), also the Váh River basin was heavily damaged by a flood on July 3–5 (Pekárová et al., 2011). In 1594, it was ordered to clean the banks of the Danube River in Komárno from tree trunks, which had been deposited here during large floods (Alapy, 1933). In 1595, the Danube flood swept away all the bridges except that in Regensburg in Germany (Tóry, 1952). In 1598 imperial military became captured for a month in the Žitný ostrov Island due to the Danube flood. High water was also recorded in the Váh and Hron river basins in October 1599. In 1614, large flooding occurred in the Hron River (Graus, 2002), and in December

1619 on the Danube River. The Váh River was also in flood on August 20 and 21, 1620, like on the same month in the following year, when there were even several flood waves in the summer season (Réthly, 1962). Another flood occurred on the Danube River in 1622.

#### PERIOD OF THE 1660s-1850s

The last period of accelerated fluvial processes within the LIA falls into the 1660s–1850s. This period has been comprehensively studied on the Danube River, where also the most prominent geomorphic response is evidenced by historical maps and additional data. Although such analysis is missing for the Váh River and other Slovak rivers as yet, during this period three exceptional flood events occurred, namely in 1662, 1725 and 1813, that must have significantly affected channel morphology of several rivers.

Within this period, two stages of significantly accelerated fluvial activity are clearly distinguished. The first one in the 1660s–1730s is partly correlated with a cooling phase corresponding with the Maunder minimum of sunspot numbers (1645–1715 AD; Koslowski and Glaser, 1999). During this period, the course of flood waves was already significantly affected by protective embankments along some reaches (the Danube River at the upper Žitný ostrov Island). On actively meandering stretches, the rivers responded to hydroclimatic events mainly by accelerating the meander development (Pišút, 1995). Enhanced geomorphic activity of large rivers also provoked first artificial meander cut-offs, documented on the Danube River around 1730 AD (Purgina, 1958) and on the Váh River between Hlohovec and the imperial fortress of Leopoldov in 1753 AD (Arcanum, 2006b).

The second stage of the last period of accelerated fluvial activity within the LIA is dated to the 1760s–1850s, being well correlated with its last spell. Geomorphic response of rivers to floods of this period was already significantly affected by generally increasing surface runoff, in relation to land use changes and introducing new crops (potatoes, corn, beet). In that very period (the

1770s), also systematic interventions into river channels began that significantly affected the bedload regime at the downstream of regulated stretches and further increased the instability of channels. These included artificial cut-offs, the first side-channel closures and construction of groynes in order to improve navigability, facilitate river transport, and to protect exposed riverside settlements. Natural changes and human interventions also resulted in substantial simplification of floodplains and water concentration into the main channels (Pišút, 2002).

This second stage of accelerated fluvial activity was particularly characterised by a higher frequency of cold to severe winters, leading to frequent major ice- and snowmelt floods. Within this period, the cluster of largest winter-type floodings occurred in the Danube River since the 1516, 1526 and 1740 events - on February 1775, 1780, March 1784, February 1799, January 1809, 1813 and 1830 (February), 1838 (March), and 1850 (February), including some of the most catastrophic events that successively brought damage and destruction to Bratislava and Komárno (1809), Vienna (1830), as well as Buda and Pest (1838; Tóry, 1952; Réthly, 1970; Pišút, 2006, 2008, 2009). During 1818–1895 period, ice occurred on the Danube in 52 from a total of 72 years and the river was frozen on average 32 days a year (Földes, 1896).

Extreme floods due to heavy regional rainfall that occurred during this period, include the most disastrous Váh River flood on record in 1813 and the second largest high flow of the last millenium on the Danube River – the autumn 1787 flood (Pišút, 2011).

#### GEOMORPHIC EFFECTS OF MAJOR FLOODS IN THE STAGE OF THE 1660s-1720s

A major flood in the Hron River in April 1661 – the largest one since 1614 – destroyed almost all houses of the riverside suburb at Banská Bystrica (Graus, 2002). The following year 1662 was a memorable one in the series of extreme flood events. There was a high water on the Váh and Hornád rivers in May. However, even larger floods were produced by heavy

cloudburst in the Tatra Mts. and Levočské vrchy Mts. region on August 5 and 6. They hit the catchment areas of the Váh, Poprad and Dunajec rivers and caused large floodings in the Váh valley and in Poland, as well. During these floods, the village Chmelnica was destroyed by the Poprad River and the channel was shifted by 800 m (Horváthová, 2003; Pekárová et al., 2011). Heavy damage was inflicted to the towns Kežmarok, Levoča and several villages in Spiš county; e.g., at Holumnica, a local brook destroyed a church and a belfry (Réthly, 1962).

The Orava River was swollen in August 1663 and the flood was also repeated in the same month a year later (1664). Moreover, there was also a flood on the Váh River in September. The Váh was strongly swollen in the autumn of 1672 and in 1683, as well.

In the case of the Danube River, Bratislava was hit by several major floodings, e.g., in 1650, 1670, 1672 and 1682 (June). In the memorable year of 1670, after a major ice flood in March, the Danube stretch between Bratislava and Komárno was badly hit by the

major flood in July. Extensive flooding of the Žitný ostrov Island reportedly claimed 500 lives and also 4,000 pieces of livestock drowned (Meyer and Geiger, 1677). According to Pekárová (2010), the peak discharge of this flood overtopped that of the 1899 flood ( $> 10,870 \text{ m}^3 \text{ s}^{-1}$ ).

The floods of this season may have determined the more evenly distribution of the discharge among three main Danube anabranches; the decades 1660s–1680s represented a period of culminating discharge or enhanced water capacity of the Lesser Danube anabranch (refs. in Pišút, 2006). In addition, some conspicuous avulsions and meander cut-offs are dated to this period (Földes, 1896). In this time span, also a new course of the Lower Nitra River was produced and a 20-km-long Lower Žitava River (*Schüttel Vag*, 1661) became abandoned (Fig. 2). Into the period of the late 17<sup>th</sup> century – 1753 AD also falls a cluster of successive cutoffs near the village of Bodíky (Pišút, 1995), possibly indicating extreme flood events or altering effective discharge (cf. Hooke, 2004).



Figure 2. The character of the Danube River channel during the time period of new fluvial activity. Main distributary anabranches and several – no longer existing – minor channels at the largest Slovak alluvial fan of the Danube River downstream of the Devín Gate. Map of 1670 showing Žitný ostrov Island (in Slovakia) and Szigetköz Islands (in Hungary) with adjacent alluvial territories (Arcanum, 2007)

Heavy lateral erosion is indicated on historical maps by extensive areas of point and mid-channel bars (cf. cartographic evidence cited in Pišút, 1995, 2006).

Of only a smaller scope as of the April 1661 flood, were the Hron River floods of July 1692 and November 1700, May 1710, and September 1713 (Graus, 2002). Severe ice floods occurred in the Danube River in 1709, 1710, 1721, 1722 and 1729 (Réthly, 1962; Földes, 1896). A major flood occurred in May 1730. In 1720, both the Váh and Morava rivers (at Skalica) were swollen. In 1728, the Poprad River flooded on August 30 in Kežmarok. In January of the following year, the Hornád River flooded at Košice (Réthly, 1962).

Disastrous floods also occurred in 1725, when even three flood waves originated after the long lasting rainfall in the upper Váh and Poprad catchments, the largest event since the floods of 1662. The first wave peaked on May 28 and 29. During the second wave on August 5 and 6, the flooded brook Smrečianka (the right-side tributary

of the upper Váh River with a basin in the Western Tatra Mts.) swept away around 100 bodies from local cemetery in Okoličné. The catchments of the Orava, Torysa and Hron rivers were also hit by flood. The third wave occurred on September 4 to 7 (Graus, 2002; Horváthová, 2003, Brázdil et al., 2008).

#### GEOMORPHIC EFFECTS OF MAJOR FLOODS IN THE STAGE OF THE 1760s-1850s

The chronological sequence of natural channel changes affected by floods and amplified by human works has been documented at the Danube River in Bratislava. Floods of the 1760s–1770s triggered the series of subsequent channel adjustments, leading to permanent instability of the river channel. During the flood in June 1771, the water reached its maximum level since 1736. Natural switch of the main channel in 1766–1774 enabled the construction of protective and transport levee, the so-called Vienna highway; successive blockage of a major secondary channel in 1777 resulted in the flow concentra-



Figure 3. Breaches to the side-channel closure (and dike) at the village of Rusovce (Carlburg), illustrating the destructive force of the 1780 and 1784 ice floods. Heavy lateral erosion in re-activated channel during these high flows was also indirectly evidenced by extensive non-vegetated bars (Arcanum, 2006b)

tion, riverbed degradation and shortening (Pišút, 2002). Increased channel gradient and competence contributed to rapid formation of brand new bends downstream near Rusovce (Pišút and Timár, 2007) and at the village of Čunovo prior to 1790, where the eroded banks were retreating by a rate of up to 72 m a year (!) during 1783–1794 period (Pišút, 2008). Increasing river activity from the 1760s onward with peaking values in the 1780s was also indicated by erosion rates from the Bratislava reach, which gradually increased from 11.7 m yr<sup>-1</sup> (over 1712–1753 period) up to 37.03 m yr<sup>-1</sup> in 1774–1779 pe-

riod (Pišút, 2002). The decade of the 1780s was exceptional as to the major and geomorphologically effective floods (Fig. 3). A major flood at the turn of October and November 1787 was possibly the second largest one of the last millenium at the Danube with a character of 200–500 yr flood and estimated peak discharge of at least 11,800 m<sup>3</sup> s<sup>-1</sup> in Bratislava, and it also had a significant geomorphic effects (Pišút, 2011).

Downstream of Bratislava, channel adjustments eventually resulted into a dramatic planform change from actively meandering to braided in the 1780s, when a series

Table 1. The 1770s–1790s floods of the Slovak rivers according to the data compiled by Réthly (1970)

Year	Month	River	Note
1763	May	Váh basin	
1774	July	Poprad	
1775	February	Váh	
1776	February	Váh	Sereď, bridge destroyed
	July	–//–	
1777	June 2.	Biely Váh	at Vážec
1778	April	Váh	
1779	August 11. – 18.	Váh	at Trenčín
	November 26.	Váh	at Trenčín
		Hron	at Banská Bystrica
	December	upper Váh, Boca stream	
1780	October	Latorica	
1781	June 13.	Uh	
	July 11.	Ondava	at Prešov
	September	Hornád	
1782	May	upper Váh, Belá, Hornád, Torysa	
1784	March 28. – 31.	Váh, Poprad, Slaná, Nitra	
1789	August 7	Poprad	this flood overcame that of 1774
	August 23. – 25.	Poprad, Hornád	
1790	July 20.	Topľa	
1798	March	Váh	at Nové Mesto, Sereď
	September 1.	upper Váh catchment	Liptov county
1799	April 16.	Rimava	at Rimavské Brezovo
	April 30.	Bodrog	
	August 12.	Bodrog	at Šarišský Potok

of large meanders were cut-off. Instead, numerous non-vegetated bars appeared as a sign of channel over-enrichment with bedload, that caused bilateral channel widening and related damage to dikes (Földes, 1896; Pišút, 2006). Active meandering still persisted farther downstream, where two pronounced meander loops near the village of Čičov were quickly developing until they had been artificially cut-off in 1798 (Timár and Pišút, 2008). Major floods of this period were also responsible for deposition of massive gravel accumulations dated to the 1790s–1820s (Pišút and Timár, 2007).

In the first half of the 19th century, the Danube main channel in Slovakia was

a high-energy river with braided channel planform. Multiple shallow channels with many bars used to freeze easily, thus providing an ideal environment for ice jamming and possible ice floods (cf. Pišút, 2009).

Also in other rivers accounts on floods considerably increased from 1770 onward (Tab. 1). In the case of the Váh River, the largest geomorphic fluvial effects were undoubtedly linked to the most catastrophic flood on record in Slovakia, with a character of 500–1000 yr flood on August 23–26, 1813. This flood claimed at least 243 victims, heavily damaged or even obliterated more than 50 villages, pulled down bridges, destroyed and/or damaged important public buildings

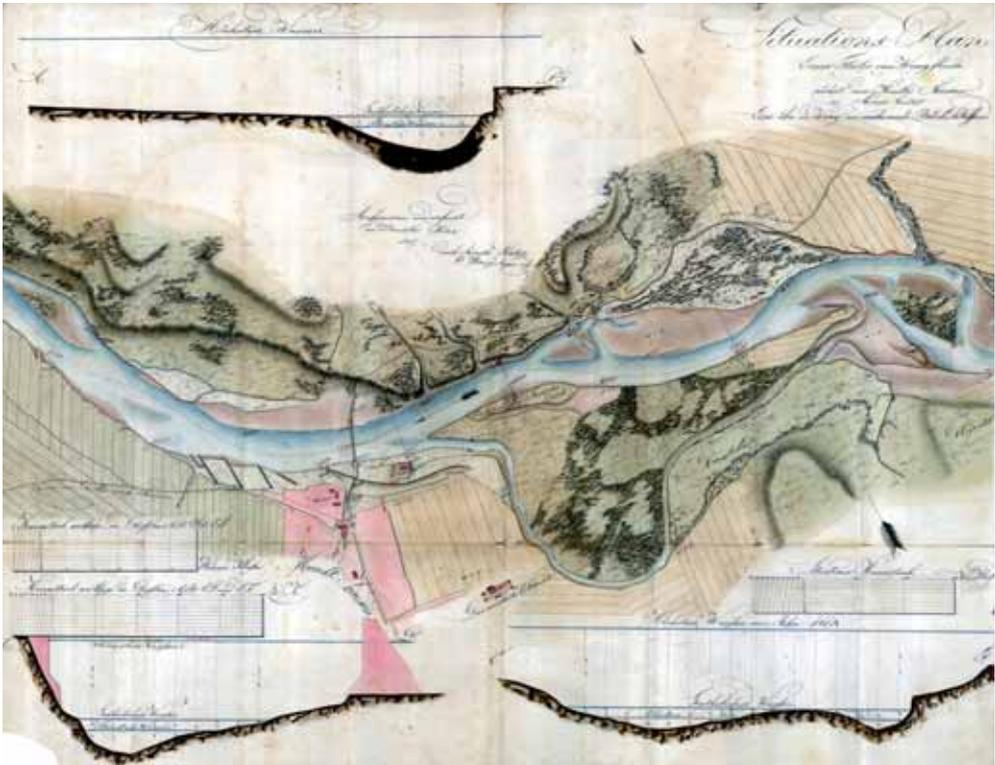


Figure 4. Stretch of the Váh River near Sučany in 1817, with representation of the water levels during the “millennium” flood in August 1813, which were extraordinary high in this partly-confined valley river setting. The situation plan also shows some other details, illustrating devastating effects of the flood, such as the remnants of the old bridge, which had been destroyed by the flood. Also the salt distribution warehouse building had to be dislocated to a new safer position due to this flood (Arcanum, 2006b)

(e.g., distribution warehouses of salt; Fig. 4) and initiated several landslides. New bars and alluvial islands appeared in the Váh channel, whereas extensive areas of the floodplain (fields, meadows, orchards) were covered by gravel and sand. This flood was caused by heavy regional rains lasting 56 hours in the Tatra Mts. that also hit the basins of Poprad, Slaná, Hornád and Hron rivers. The Poprad River bed was left blocked with large boulders to such an extent that it had to be abandoned as a traditional waterway to the Halič region in Poland (Horváthová, 2003). The largest flood since that of 1813 was in July 1845, which hit extensive area of Slovakia, including the basins of Váh, Poprad, Slaná, and Hornád rivers. Disastrous floods in the Hornád River basin occurred in 1816 and 1817.

Within this period, a conspicuous changes of the Váh channel occurred along its middle and lower reach (Arcanum, 2006a, b, 2007). For example, at Trenčín the channel seems to have transformed from the actively meandering one in the 1770s to a wandering channel pattern of the early 19th century. Along the lower stretch at Leopoldov, the

river changed from actively meandering, high-sinuosity river in 1775 into a low-sinuosity river, oversaturated with bedload due to the March 1830 flood (Arcanum, 2006b).

A major flood in the Hron River occurred also on May 8, 1853 (Munkáči and Rigo, 1998). Not much lesser in scope that the flood of 1813 was a Váh River flood in August 1854 (Bitara, 1998), which destroyed almost all bridges across this river in the Lip-tov county. It also hit the basins of the Poprad, Hnilec and Torysa rivers (Horváthová, 2003). A good example of local catastrophic flood from this period is provided by the event of June 11, 1848 from Štefanová near Terchová (Malá Fatra Mts.), which claimed 14 lives (Pekárová et al., 2011).

#### RUNOFF PROCESSES: GULLYING AND MUDDY FLOODS

Permanent gullies in Slovakia represent in fact geomorphic effects of historical gully erosion. The spatial distribution of gullies in Slovakia, according to their density, is depict-

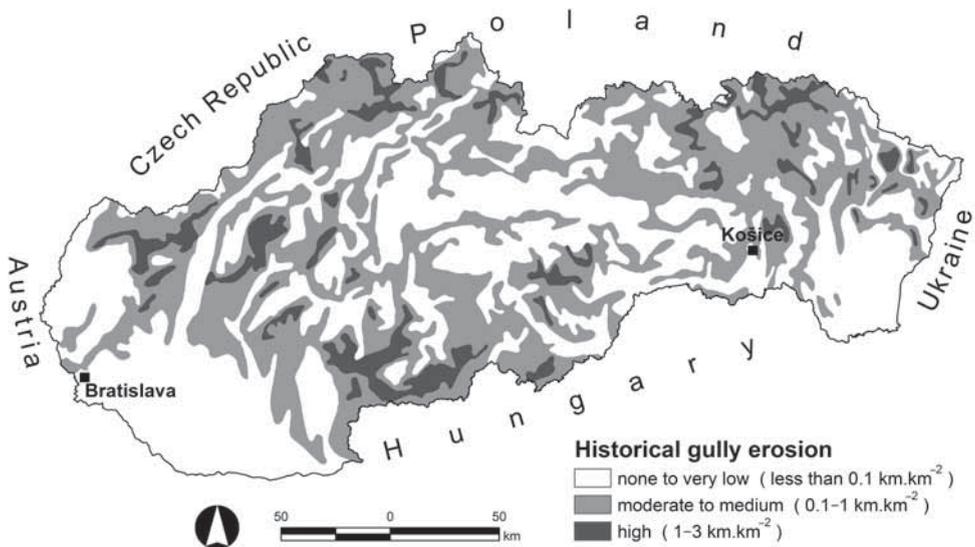


Figure 5. Map of density of permanent gully network formed by historical gullying (figures in brackets mean total lengths of gullies in kilometres per introduced area unit) (Fulajtár and Janský, 2001; according to Bučko and Mazúrová, 1958)

ed on the unique map by Bučko and Mazúrová (1958) at the scale of 1: 400,000 (Fig. 5). The densest gully network is linked to uplands and hilly lands where above all two factors influenced the activity and effectiveness of concentrated runoff: a deep regolith in areas built of less resistant (flysch and volcanic) rocks and land use (mostly pastures and arable land).

Not fully clarified remains the question when permanent gullies were formed. Some historical framework of gully formation in Slovakia was already indicated by Bučko and Mazúrová (1958) who suggested that overgrazing, associated mostly with the Walachian colonization and the “kopanitse” settlement, resulted in the formation of a dense road and path network that controlled gully formation on deforested slopes. Unfortunately, they did not date the gulying itself. According to Midriak and Lipták (1995), the accelerated water erosion (including gulying) was a frequent phenomenon in the period of the last three centuries.

The most important attempt to assess the geomorphic effect of the historical gully erosion and especially to constrain (at least relatively) the age of the gully formation was done in the Myjava Hilly Land in the western Slovakia built predominantly of flysch-like rocks (Stankoviansky, 2003a,b,c). The average gully density in this area is ca 1.2 km km<sup>-2</sup> (Stankoviansky et al., 2007), while extensive islands show values of 2–3 km km<sup>-2</sup> (Bučko and Mazúrová, 1958) and the field research revealed the maximum local density of even 11 km km<sup>-2</sup>. The gully depths are commonly up to 10–15 m, but exceptionally exceed 20 m. The pattern and density of these gullies have been controlled primarily by artificial linear landscape elements typical for the original land use from the pre-collectivisation era, such as access roads, field boundaries, lynchets, drainage furrows, etc.

Research revealed at least three phases of disastrous gulying in the Myjava Hilly Land. The abandonment of some villages in the 14<sup>th</sup> century in the western margin of this area may suggest the effect of the earliest phase. The evidence for it is most convinc-

ing in the villages of Kratnov and Hlboké, which were situated on the bottoms of dry valleys now cut by distinct thalweg gullies. Stankoviansky (2003a,b) supposes that gullies coming from this period were probably later filled, but reactivated locally during the later phases of gulying. Similar development of gullies is also supposed to typify other parts of Slovakia with the settlement older than that from the 14<sup>th</sup> century.

This oldest stage of gulying could have manifested itself only in marginal parts of the Myjava Hilly Land that were already settled at that time. No gulying could have affected its forested central parts. This situation started to change in the course of the 16<sup>th</sup> century. Conditions for gully erosion were created here by extensive forest clearance by the “kopanitse” settlers enlarging the area of farmland, as well as by the Walachian shepherds acquiring pastures. The “kopanitse” colonization took place in this area in the period since the second half of the 16<sup>th</sup> until the end of the 18<sup>th</sup> centuries, the wave of the Wallachian colonization started here at the end of the 16<sup>th</sup> and culminated in the 17<sup>th</sup> centuries.

The old military maps from years 1782, 1837 and 1882 and both regional and local historical sources indicate at least two further periods of gully formation, the older sometime between the mid-16<sup>th</sup> century and the 1730s, and the younger one between the 1780s and the mid-19<sup>th</sup> century. Gullies were formed and increased in stages, but neither of them affected the whole of the study area. The identified local disparities in the increase of gully network suggest that the gully growth was not area-wide in individual stages. The triggering mechanisms of gulying was represented by extreme rainfalls and snowmelts during the Little Ice Age *sensu stricto*. In particular, colder and wetter fluctuations with increased precipitation totals and greater probability of increased frequency of significant events provided more opportunities for gully formation (Stankoviansky, 2003a,b,c). It is in accordance with the opinion of Starkel (1998, 2000) that the ideal conditions for

rapid development of gullies are particularly represented by repetitions of the sets of extreme rains, which were frequent just in the course of the LIA.

Similar conclusions as to the linkage of disastrous gully erosion to the LIA were reached also by Šindlerová (2005) in the eastern part of the Zvolenská kotlina Basin, central Slovakia, and by Papčo (2010) in the northern part of the Nitra Hilly Land, Danube Lowland. Both authors used the aforementioned analysis of old military maps. According to the former, all gullies in the studied part of the Zvolenská kotlina Basin below the Poľana Mts. were formed between the 1<sup>st</sup> and 3<sup>rd</sup> mapping. According to the latter, gullies in the studied part of the Nitra Hill Land originated at least in two phases, namely before the 1<sup>st</sup> and between the 1<sup>st</sup> and 2<sup>nd</sup> military mapping. Opening of profiles on the colluvial fan below the investigated gully close to the village of Prašice in this area, the analysis of correlative sediments, archaeological dating, and especially <sup>14</sup>C dating of charcoal in buried fluvisol made it possible to fix the beginning of deposition of the eroded material from agriculturally used valley slopes to the valley bottom since the 14<sup>th</sup> century (Papčo, 2010).

Gully erosion was accompanied by muddy floods. Muddy floods signify water flowing from agricultural fields carrying large quantities of soil as suspended sediment or bedload (Boardman et al., 2006). Thus, this phenomenon is not connected with permanent watercourses, but exclusively with cultivated slopes. The more intense erosion is, the more extreme examples of muddy floods occur. Muddy floods were very frequent phenomena in the LIA period and their effects corresponded with the presence of gullying. The biggest muddy floods in this period accompanied disastrous gully erosion events and also the stages of increased activity of muddy floods corresponded with those of gullying.

According to Stankoviansky (2002), the geomorphic effects of muddy floods in the LIA period in the Myjava Hilly Land were marked by an increase of the surface of main valley bottoms due to accumulation of mate-

rial coming mostly from gullies, representing locally up to 3 m-thick-beds of alluvial sediments. Repeated muddy floods generating in gullies also left thick bodies of colluvial cones prograding onto the floodplains of the valleys where the gullies emptied. It is supposed that the above mentioned disappearance of some villages in the 14<sup>th</sup> century in the marginal part of the Myjava Hilly Land was influenced, besides gully erosion itself, also by gullying-driven muddy floods (Stankoviansky, 2009).

### **GRAVITATIONAL PROCESSES: DEBRIS FLOWS, LANDSLIDES AND ROCKFALLS**

Debris flows represent the most dynamic, high-energy gravitational processes in the cryonival system of the Slovak Carpathians and in particular in the Tatra Mts. The main cause of debris flow formation is extreme precipitation of high intensity, reaching great efficiency during a relatively short time. Debris flows operate exclusively above the upper timber line and damage rather extensive areas. Their geomorphic effects are marked mostly on talus cones.

According to Kotarba (2004), the most important study site from the viewpoint of reconstruction of landform changes in the Tatra's environment as a whole is the Dolina Zeleného plesa Valley in the Slovak part of the High Tatra Mts. Detailed studies of this author (Kotarba, 2004, 2005, 2007a, b) in the area of the Zelené pleso Lake revealed the changing intensity of debris flows in the past with changing climate. The rates of debris flows varied during and after the LIA that occurred in the Tatra Mts. in the period of 1400–1925 AD. Marked climatic anomalies during the LIA resulted in much more frequent occurrence of debris flows as well as in their higher force and energy than in the later period. Analysis of lacustrine sediments confirmed that the high frequency of high-energy, rapid slope movements in the Tatra Mts. took place between 1400 and 1860 AD. Activity of debris flows continued until the end of the LIA, mostly in its

final phase, approximately in the period of 1900-1925 AD, but already with lesser intensity. The dynamics of debris flows in this period was confirmed, besides the analysis of lacustrine sediments, also by lichenometric dating. It showed that debris flows older than 1800 AD do not occur on the surface as they were buried below debris flow bodies coming from the 19<sup>th</sup> and 20<sup>th</sup> centuries (Kotarba, 2004).

Perhaps, the best known debris flow event in the Slovak high mountains during the LIA period happened in the Malá Fatra Mts. in 1848. It destroyed the village of Štefanová under Veľký Rozsutec Mt. (1610 m a.s.l.) (Stankoviansky and Barka, 2007).

The Slovak literature lacks mentions on landslides from the LIA period, though – according to Stankoviansky and Barka (2007) – they must have been activated indubitably in this more humid spell, like other above mentioned precipitation-induced geomorphic processes. The idea of reactivation of older landslides was raised as early as by Andrusov (1931), who studied these phe-

nomena in the Orava River basin. According to him, landslides were formed in part in the Pleistocene and in part in the Holocene, but some of them have been active until the present, what means also during the LIA. According to Paul (1868), numerous landslides in this area are really of historical age. The fresh landslide on the slope of the Ostražica Mt. between small towns Nižná and Tvrdošín (Oravská vrchovina Mts) is depicted on the 1834 map by F. Zornberg (Arcanum, 2006b) (Fig. 6).

The only so far found written note about the landslide from the LIA period is contained in the travel book by Mednyanský, first written in 1826 (cf. Mednyanský, 1962). The author described a devastating landslide next to the village of Vlašky in the upper Váh River valley, Liptovská kotlina Basin, in 1813. The landslide was initiated by an extreme rainfall bringing about the worst known flood on this river.

Historical records refer also to some rockfalls that occurred in the highest parts of the Slovak Carpathians in the LIA pe-

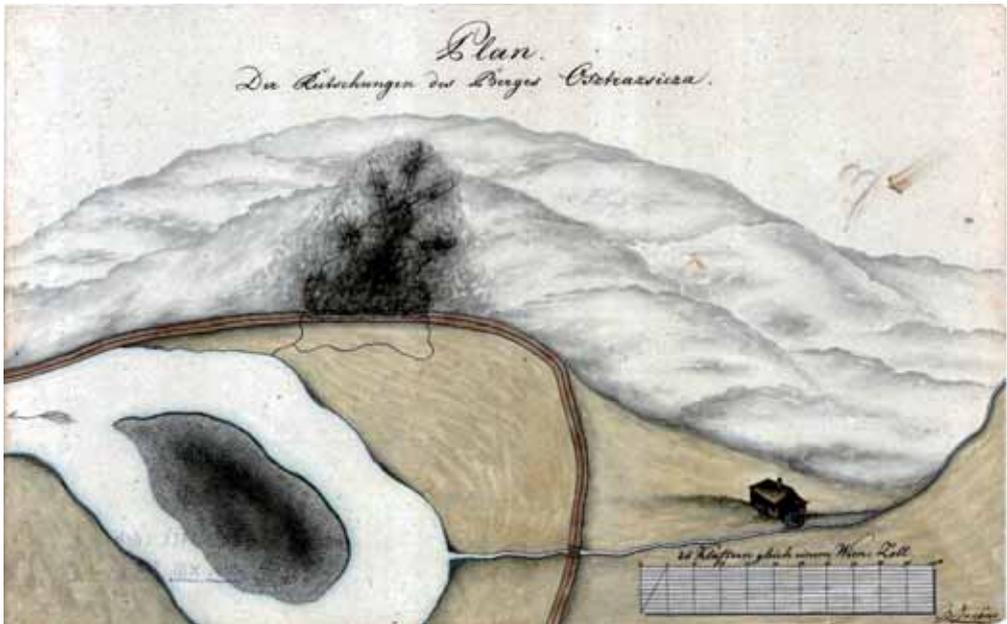


Figure 6. Landslide on the slope of the Ostražica Mt. (Oravská vrchovina Mts.), depicted on the 1834 map by F. Zornberg (Arcanum, 2006b).

riod. The oldest rockfall affected peaks of Gerlachovský štít (1590 m a.s.l.), Lomnický štít (1662 m a.s.l.) (cf. Špúrek, 1972), and Slavkovský štít (1662 m a.s.l.) (cf. Kotarba, 2004) in the High Tatra Mts. However, at least in the case of the 1662 event, the rockfalls are attributed to possible earthquakes besides disastrous rainfall (Réthly, 1962). According to Kotarba (2004), in the Dolina Zeleného plesa Valley, the period 1676-1900 AD may be interpreted as the main phase of rockfall/rockslide activity with the culmination between 1850-1900 AD. He also states that these processes were controlled both by climatic factors and earthquakes.

## CONCLUSIONS

The geomorphic response to the LIA in Slovakia, understood roughly from 1250 to 1890 AD (in the case of the Tatra Mts. from 1400 to 1925 AD), represents increased occurrence and effectiveness of precipitation-induced geomorphic processes, namely fluvial, runoff and to a certain degree also some partial gravitational processes. Geomorphic effects and environmental impact of these processes became significantly enhanced due to the synchronism between climatic fluctuations and periods of increased human interference. As to fluvial processes, four periods of their increased activity were identified, being linked with increased frequency of big floods in the periods of (1250) 1378-1526 AD, the 1560s-1570s, the 1590s-1620s, and the 1660s-1850s, while the last period shows two stages, namely the 1660s-1720s and the 1760s-1850s. There were also identified three periods of disastrous gully erosion accompanied by muddy floods in the LIA period, namely in the 14<sup>th</sup> century, between the mid-16<sup>th</sup> century and the 1730s, and between the 1780s and the mid-19<sup>th</sup> century. It is obvious that periods of increased activity and geomorphic effectiveness of both fluvial and runoff processes are in temporal conformity or, in other words, both processes operated hand in hand in the affected areas. As to debris flows, their high-

est activity in the Slovak part of the Tatra Mts. within the LIA finished in the 1860s. Sparse mentions on particular events of debris flows, landslides or rockfalls triggered by heavy rainfalls are mostly linked with simultaneous occurrence of floods in their surroundings. Broader understanding of the LIA enables us to join into one period the 3<sup>rd</sup> and 4<sup>th</sup> of the four above-mentioned prehistoric and historic periods of accelerated precipitation-induced processes controlled by synchronous occurrence of climate changes and human interference.

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