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River channel deformations under different phases of hydrological regime and various energy floods

Abstract: The paper presents the results of the regular bank erosion monitoring on three rivers of the Eastern European (Russian) Plain: the Kerzhenets River (left tributary of the Volga River), the Sherna River (left tributary of the Klyazma River) and the Tarusa River (left tributary of the Oka River). The first two rivers are characterised by wide floodplains and meandering channels, the third one is distinguished by an incised straight channel and a narrow floodplain. Results of the bank erosion monitoring carried out twice a year – after a spring snowmelt flood and a summer low-water period – over the last 5–15 years allowed the authors to arrive at the following conclusions:

1. Bank erosion and channel lateral migration were observed only during the flood events. No channel deformations were observed during the low-water periods on the rivers of the humid temperate climate zone.

2. Bank erosion and channel lateral migration were observed only during the years with the highest flood magnitude, regardless of the stream bed sediment grain size composition. In the years with moderate flood events, bank erosion occurred, but its rates were inconsiderable and comparable to the measurement accuracy limit. During dry years, no channel deformations were observed.

3. As a consequence of the meander development and its sinuosity changes, zones of the maximum concave bank retreat change their locations along the meander. First, the maximum erosion rate zone occupies most of the concave bank length, then moves towards the lower limb and concentrates at the meander apex when reaching the maximum sinuosity.

4. Formation of cutoffs in a high-sinuosity meander is mainly associated with intrinsic mechanisms of the meander self-development and to a lesser extent with a flood magnitude. In this case, the main factor of the cutoff process is a very fast increase in the channel longitudinal profile gradient, rather than flood discharge.

Keywords: floodplain, river alluvium, horizontal deformations of river channel, erosion of river banks, flash floods.

1. Introduction and scope of the research

Fluvial processes are among the most dynamic geomorphic processes. Unconfined lowland rivers with unconsolidated floodplain banks can change their channel patterns very rapidly, basically within a few years. Such changes are associated with bank erosion, meander cutoffs, shifts of the main flow from one arm to another. A number of gradations have been proposed for the quantitative classification of bank erosion and lateral channel deformation rates. The most widely accepted in Russia is as follows: $< m \cdot year^{-1}$; $m \cdot year^{-2} – m \cdot year^{-5}$; $m \cdot year^{-5} – m \cdot year^{-10}$; $> m \cdot year^{-10}$ (Morphology and dynamics of river channels of the European part of Russia and neighbouring states, 1999). This quantitative classification of channel migration rates is used for small-scale mapping of river channel processes as well as for assessment of environmental hazards and risks associated with bank erosion and lateral channel deformations.

At the same time, it is often difficult to determine what time and space intervals can be assigned to given values. Do they really represent the gradual bank retreat up to 2, 5 or 10 m over the annual period or much faster erosion over a shorter phase of the hydrological year? Are such values applicable to each bank section within a river's reach, or to some particular parts only?

The answer to the second question is relatively easy and straightforward. The eroded bank sections are located at particular parts of the channel, largely controlled by its planform and morphological pattern. Such locations include concave banks of meanders, banks in arms opposite to braid bars or islands, upstream or downstream ends of braid bars or islands. They are described in detail in classic textbooks on river channel processes, hence it is obvious for specialists that both qualitative and quantitative characteristics of bank erosion are applicable to them (Chalov, 2016). Some of the maps and published databases on hazards associated with channel processes contain information on a relative length of actively eroded bank sections for particular morphologically uniform river reaches, separately for right and left banks. In addition, it is usually implied that the reported bank retreat rates are attributed to zones with the maximum intensity of this process, such as bank convexities at meander apexes, flow separation zones at upstream ends of braid bars or islands, other bank sections directly affected by the main flow dynamic axis. It is obvious that the adjacent bank sections oriented differently towards the main flow may experience much lower erosion rates or even be stable.

As regards the temporal variability of bank erosion rates, the only way to precisely determine the duration of active bank retreat and its real intensities during such periods is to conduct regular monitoring observations. In order to cover a large variety of conditions for lowland rivers of the temperate humid climate zone, it is necessary to consider different lithological conditions of channel deformations at morphodynamically typical channel sections. Measurements of bank retreat rates are usually carried out once a year and later compared with snowmelt flood discharges, the presence and discharges of rainfall-induced floods for a particular year.

Three rivers have been selected for regular monitoring: a medium-sized river – the Kerzhenets River – with an unconfined channel and sandy bed material, a small river – the Tarusa River – with a confined channel in a narrow valley and gravel bed material, and another small river – the Sherna River – with an unconfined channel and sandy bed material.

2. Results

2.1. The Kerzhenets River

Monitoring of the Kerzhenets River has been carried out since 2001. The retreat of eroded concave banks has been observed at three meanders: the low-sinuosity segment-shaped meander (l/L = 1.2)[1], the high-sinuosity segment-shaped meander (l/L = 1.5) and the high-sinuosity finger-shaped one (l/L = 2.0). Trees marked at a remote safe distance (> 15 m) from the upper break in the eroded bank were used as fixed points for repeated measurements. The relative height of the eroded bank above the mean low-water level (MLWL) is 3-4 m. Initially, from 2001 to 2006, measurements were carried out twice a year – in June, after the spring flood recession and in September, after the summer low-water period (LWP), sometimes interrupted by rainfall-induced floods.

The comparison of bank retreat rates measured for different years and different hydrological regime phases has shown that this process basically occurs only during the spring snowmelt high-water period (HWP). During the summer LWP, bank erosion was not observed despite the fact that several rainfall-induced floods did occur (Fig. 1) (Korableva and Chernov, 2008). It should be noted that for some fixed points, changes in the distance to the eroded bank's upper break are within the measurement error or can be related to local mechanical disturbances other than the undercutting by the river flow. Therefore, regular observations after the summer LWP were ceased in 2007, while regular measurements after the spring HWP have been continued until today.

A high degree of annual variability in the bank erosion rates has been observed from the basically stable situation up to 1 m·year^{-1} bank retreat. An attempt has been made to correlate

[1] l/L – meander sinuosity or path length to wave length ratio, where l – meander path length, L – wave length.

the measured values with the spring HWP water levels for the Kerzhenets River (Fig. 2). It appears from the diagram that noticeable bank erosion (average for the total length of concave banks of all three meanders under observations) occurs only during high spring floods when the maximum water level exceeds 3-4 m above the temporary gauging station 0 level (2001, 2005, 2012, 2013 yr). There is a strong positive correlation between the water levels and the mean concave bank retreat rates (Korableva and Chernov, 2012) (Fig. 2). At the same time, the average value of the bank retreat rate for the whole monitored section over the entire period of observations (2001–2015) is 1 m·year$^{-0.7}$. This single figure is not representative of the bank erosion observed at different locations within the monitored section or years with different hydrological conditions.

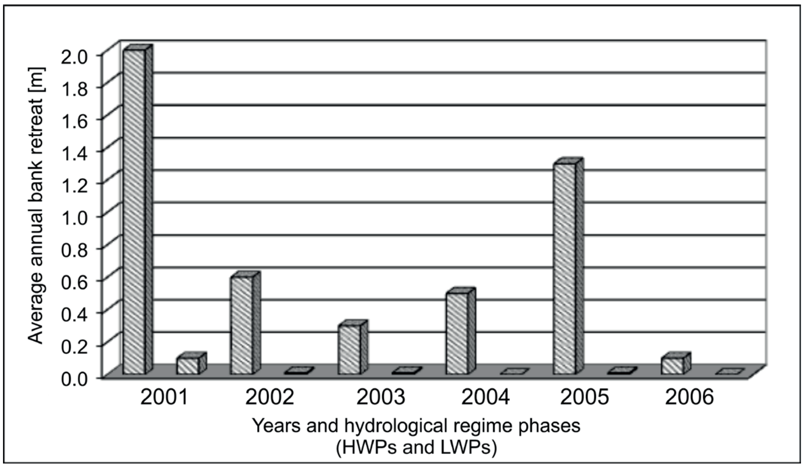

Figure 1. The Kerzhenets River floodplain bank retreat during HWP and LWP for wet years of 2001, 2005 and dry years of 2002, 2003, 2004 and 2006

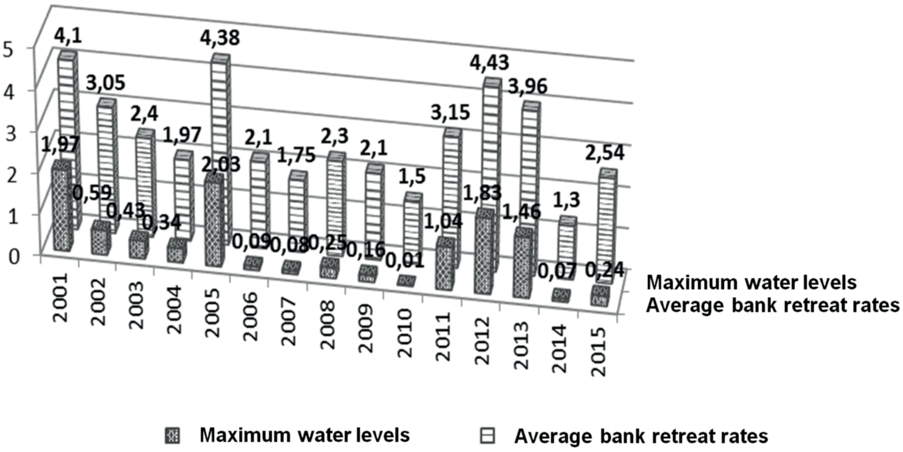

Figure 2. Maximum water levels and mean bank retreat rates for three meanders of the Kerzhenets River for the 2001–2015 period

In addition, certain differences in the concave bank retreat rates and the locations of the most intensive undercutting have been determined, depending on the meander sinuosity for the studied reach of the Kerzhenets River. According to the existing knowledge about the evolution of unconfined channel meanders, there is a hydraulically optimal meander planform, i.e. the high-sinuosity (or well-developed) segment-shaped one (l/L about 1.57). Such a channel planform allows transportation of the maximum amount of both suspended and bedload sediment within a wide range of water levels (Chalov et al., 2004). One of the studied meanders is close to this optimal parameter (l/L = 1.5). The concave bank section with the highest observed retreat rates is situated at the meander lower limb where maximum bank erosion rates were observed for the years with a severe spring snowmelt flood (5.7 m in 2001, 6.6 m – 2005, 7.2 m – 2012, 4.2 m – 2013), while the average erosion rate for the entire concave bank section of the same meander was estimated as 1 m·year$^{-2.2}$.

For the high-sinuosity segment-shaped meander, it has also been found that the width of the maximum bank retreat zone increased over the period of observations, expanding transgressively from the meander lower limb towards its apex. The maximum retreat of the concave bank was observed in 2005 (7.1 m at the meander apex and 7.9 m at its lower limb), 2012 (8.6 and 9.9 m) and 2013 (4.7 and 3.2 m), while average values over the study period are 1 m·year$^{-1.8}$ and 3 m·year$^{-3.3}$, respectively.

For the low-sinuosity segment-shaped meander, the situation was somewhat different, as the highest bank retreat rates during the high-flood years were always observed along its relatively long section centred at the meander apex (4.9 m in 2005, 6.4 m – 2012, 5.0 m – 2013). This meander has not yet reached a clearly bent planform. It can be expected that the continuous process of concave bank erosion along such a prolonged concave bank front will result in the increasing meander sinuosity over the next several years. This will be followed by changes in the bank erosion pattern, with a clear differentiation of the upper limb and the minimum retreat rate, the decreasing rate of the movement of the meander apex from the early to late stages of the meander's growth and gradual migration of the maximum bank retreat zone along the lower limb, due to the increasing meander sinuosity towards the optimal value.

2.2. The Tarusa River

Similar monitoring observations have been carried out since 2010 on the Tarusa River. The monitoring site is located on the right floodplain bank, 4 km upstream of its mouth. The river valley in its lower part is generally narrow and V-shaped in the cross-section, but with a visible widening at the monitoring site. The width of the right bank floodplain is about 40 m, while the channel itself is about 20 m. Relative elevation of that particular floodplain fragment is about 4 m above the MLWL. The undercut floodplain bank exposes sandy loam (overbank sediment) underlain by gravel (stream bed sediment). The monitored bank section has a slightly concave planform. Measurements were carried out from the baseline determined by 4 fixed points dug into the floodplain surface, 4–5 m

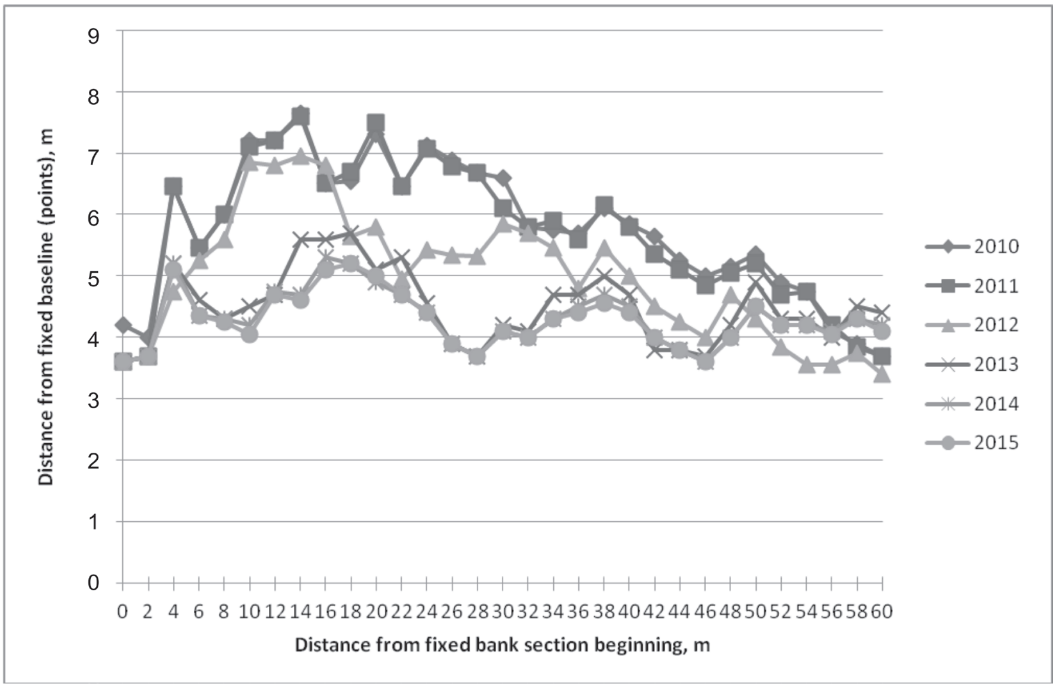

Figure 3. The Tarusa right bank deformations for the 2010–2015 period

away from the eroded bank's upper break and 20 m apart from each other along the entire undercut bank section with a length of about 60 m. Distance from the baseline to the bank's upper break was measured perpendicularly to the baseline at 2 m intervals.

The relationship between the flood levels and the bank erosion rates is equally evident for the Tarusa River as well as for the Kerzhenets (Fig. 3). The difference between the medium Kerzhenets river and the small Tarusa river is that in the case of the former, the rainfall-induced summer floods are either indistinctive or characterized by water levels on average 2.5 times lower than the spring flood, while in the case of the latter, the level of rainfall-induced floods sometimes exceeds spring floods for respective years (2012, 2013) (Fig. 4). It is evident that unlike the Kerzhenets River, bank erosion at the monitored reach of the Tarusa River can be associated both with spring snowmelt and summer rainfall-induced floods, and their relative contribution depends on hydrological conditions during the period of measurements. Unfortunately, no separate measurements before and after summer floods period have been conducted.

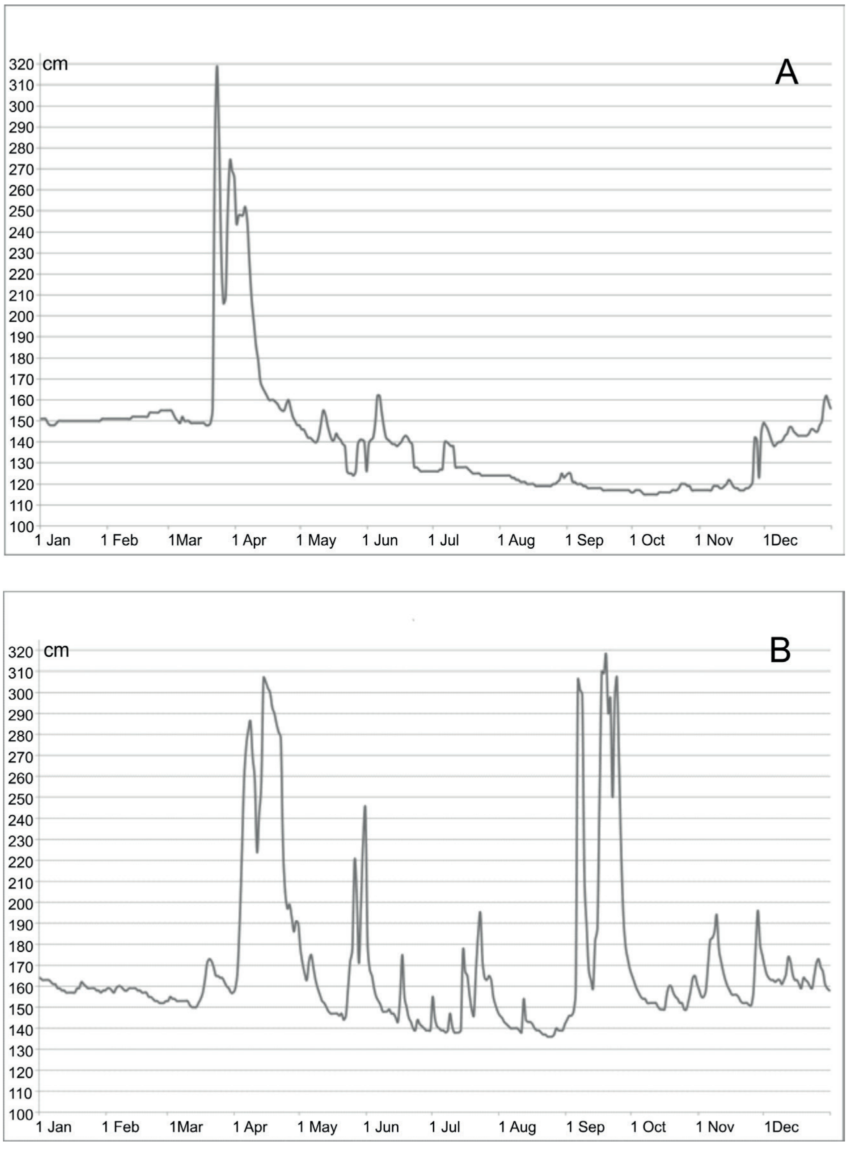

Figure 4. The Tarusa River water level curves for years without (A – 2010) and with summer rainfall-induced floods (B – 2013)

The calculation of the average bank retreat rate over the 6-year observation period gives a value of 1 $m \cdot year^{-0.34}$. This average value is significantly lower than that for the years with high flood activity (2012, 2013) and almost an order of magnitude higher than for the dry years.

2.3. The Sherna River

The monitoring of the bank erosion at the small Sherna river with the unconfined channel has been conducted since 2011. The monitored section is located within the rectangular planform complex meander containing two simple meanders connected by the straight channel section. During the spring HWP, concave banks at both meander apexes are eroded (Fig. 5). For example, the concave bank retreat in 2012 was on average 0.13 m at the upper apex and 0.32 m at the lower apex, in 2013 – 0.02 m (below the measurement precision) and 0.13 m, respectively. In 2014, the average concave bank retreat at the upper apex was 0.2 m, while the lower apex was stable. In 2015, the stability of banks was observed at both meander apexes.

Unfortunately, the water-level monitoring information for the Sherna River is not available as there is no gauging station there. Nevertheless, there is a certain correlation for the bank erosion dynamics between the Sherna and the Tarusa rivers (the latter located about 170 km southwest from the former). For both rivers, the highest bank retreat rates were observed in 2012 and 2013, characterised both by a high snowmelt discharge peak and frequent rainfall-induced floods. In contrast, bank erosion was very limited for both rivers over the next two years, which were relatively dry according to meteorological data and the Tarusa river water-level monitoring data.

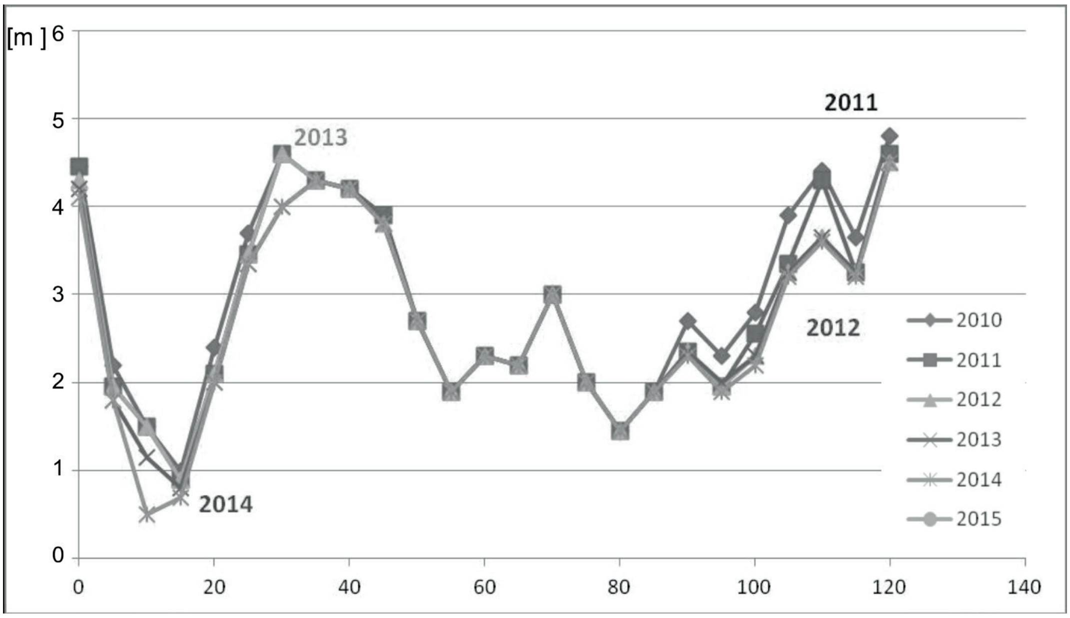

Figure 5. The Sherna River right bank deformations for the 2011–2015 period

However, the Sherna River channel experienced such a relatively rare event as a meander neck cutoff at the location just 1.6 km downstream from the monitoring site in 2012. There is a large and complex meander, also with an approximately rectangular planform, whose neck width immediately prior to cutoff was just 5.5 m, with a floodplain relative height of about 2 m above the MLWL. The floodplain is composed of sandy-loam to loam overbank deposits. During the high spring flood of 2012, a very narrow breach (3.7 m) was initially formed through the meander neck. Its development continued in 2013–2014 when the breach channel width reached 10–12 m, intercepting approximately up to 80% of the total discharge (Fig. 6). As a result, the main channel length decreased by 500 m and the long cutoff channel began to fill with deposits. The completion of this process was inhibited by the presence of wood logs in the breach channel fallen from the eroded floodplain surface at the formerly existed meander neck.

3. Conclusions

The presented results of the regular monitoring of the floodplain bank erosion, carried out over several consecutive years with clearly changing hydroclimatic regime, magnitude and frequency of floods, at rivers of different sizes, under various geomorphic and geologic conditions of channel deformations and with varying bedload sediment size, allow us to draw the following conclusions:

1. Lateral deformations of lowland river channels in humid temperate environments occur only during the high-water period (HWP): primarily during spring snowmelt floods on medium and large rivers, during both snowmelt and rainfall-induced floods on small rivers. During the low-water period (LWP), channel banks generally remain stable.
2. Lateral deformations of lowland river channels irrespective of the grain size composition of bedload sediment occur only during generally humid years with severe snowmelt and rainfall-induced floods. During the years with a moderate amount of precipitation, bank erosion occurs only locally and its magnitude is close to the measurement accuracy. Years with low precipitation are always characterized by channel bank stability. This temporal variability should be taken into account when considering the lowland river channel lateral migration dynamics, because usually only long-term mean values of bank retreat rates are considered. In fact, during the years with high precipitation, these average values may be exceeded several times, while during dry years – they are close to zero. On the other hand, such temporal discontinuity does not necessarily mean that channel deformations are exclusively associated with some catastrophic events. Wet years, for instance, with peak discharges reaching the second (medium) interval of the calculated effective channel-forming discharge (Makkaveev, 1955), have a recurrence period of 5–7 years, while catastrophic floods with peak discharges reaching or exceeding the upper channel-forming discharge interval are very rare, with < 1% excess probability (repeated once every 100 years or more). Although such catastrophic events can dramatically transform a channel and even the entire valley bottom morphology, their relative contribution over longer time spans is not so obvious. The relaxation time of the channel-valley bottom system can be quite short, because moderate but regular channel deformations rapidly restore their morphology to conditions similar to those observed before the catastrophic disturbance.
3. Zones of the maximum bank retreat rates on segment-shaped meanders with a varying degree of sinuosity are spatially associated with concave banks but locally change their locations in relation to the meander apex and limbs along with the development of a meander and its increasing sinuosity. During the initial stages of the meander growth, most of the concave bank is actively eroded, thus maintaining further meander development, its transversal and downstream migration. During the stage when a meander reaches the hydraulically optimal sinuosity, the zone with the maximum bank erosion rate shifts towards the lower limb, thus maintaining its downstream migration. Finally, the maximum bank retreat is observed again at apexes of high sinuosity meanders (finger-shaped or Ω-shaped) and the lateral growth becomes more intensive than the downstream migration. At the same time, the sinuosity continues to increase and the upper limb is approaching the lower limb, thus the meander neck becomes narrower and the probability of its cutoff increases.
4. There are different mechanisms and hence different factors responsible for these types of lateral channel deformations, such as gradual bank erosion on one side and meander cutoff by a neck breach on the other. Bank erosion primarily depends on the flow velocity. The higher the flow velocity the more intense the eroded bank retreat. There is a threshold value of the flow

velocity, below which banks remain stable. Meander neck breaches result in meander cutoffs being largely associated with intrinsic factors of meander development and less dependent on water levels and discharges during floods. Even a recently formed very narrow cutoff channel will be used as the main flow route at any hydrological stages, because its width and wetted perimeter will continue to increase, both during HWPs and LWPs. In such a case, a very fast increase in the local channel gradient becomes the leading factor rather than a flow discharge and velocity. For a certain period of the meander neck breach development, there is a positive feedback – the greater the growth in the cross-section the larger the percentage of the total discharge intercepted and even faster growth.

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