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DYNAMICS OF MEANDER DEVELOPMENT IN RESPONSE TO NATURAL AND HUMAN IMPACTS

Theses of Dissertation

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1. Introduction and research objectives

All over the world the effects of human interventions become more and more pronounced on river channels. However to reveal the rate of changes induced by these interventions is very complicated, since processes related to natural and human impact act simultaneously. Besides, anthropogenic alterations of river channels might reduce or even strengthen boost the impact of natural environmental changes.

The aim of the research is to analyse meander development influenced by natural processes and human activity on two alluvial rivers of Hungary. First of all the rate and pattern of meander development was evaluated by analysing horizontal meander parameters. The rate and pattern of the meander development varied in time and space, therefore the effects of different environmental control variables were investigated. Hydrological parameters were analysed in detail, as hydrology could change significantly during the last century. Another aim was to asses the semi-anthropogenic processes induced by river engineering works (dams, bank stabilisation), as these could also modify meander development. The final objective of the research was to delineate general development tendencies in horizontal channel changes, based on the results of the research made at different spatial and temporal scale.

The most detailed research was made on the River Hernád. Although similar measurements were carried out on the River Maros, however, here the selected reach was shorter supplying thus less data. Therefore the major part of the dissertation is based on the analyses of the River Hernád, and the results of the analysis of the River Maros are compared just in the summary.

The River Hernád is the main tributary of the River Sajó, its catchment is located in the Northern Carpathians. The variability of the water stages is high even on the lowland Hungarian section and the duration of floods is short. The hydrology of the Hungarian section is mostly determined by the Slovakian upstream catchment, however the water and sediment regimes are under considerable human influence. In the Slovakian part mostly dams and storage lakes alter the hydrology, but the effect of urbanisation (water output and input) is also considerable. On the Hungarian section 3 smaller dams were built, and on some places the channel is modified by revetments, cut-offs and flood-protection levees. The channel is highly sinuous as the result of great sediment discharge and fluctuating changeable water stages, and as far as the channel is not incised natural cut-offs occur frequently, especially during great floods.

The aims of the study could only be fulfilled by using a multi-scale analysis applying a decreasing spatial and temporal scale. First of all, long term hydrological changes, affecting the development of the whole Hungarian section of the River Hernád were analysed. The modification of horizontal meander parameters was measured on shorter reaches within a 50-years period. One of the objectives was to identify the environmental variables causing morphological changes, therefore the effects of escarpment, slope and local engineering works were also evaluated. In some meanders very detailed measurements were performed between 2008 and 2010to identify bank retreat and its influencing factors. Point-bar development was measured by dendro-geomorphology, in this case only few decades of accumulation was examined, as this measurement was limited by the lifetime of the trees.

2. Methods

The processes were studied at different spatial and temporal resolution, therefore different methods were applied at the different study sites.

2.1. Hydrological analyses

In order to characterize the hydrological changes on River Hernád in the 20th century those hydrological parameters were chosen which determine channel form. Therefore, long-term changes in the durability of different water-stages and discharges, the changes in the yearly highest and lowest water-stages and the modification of the annual water regime were determined. Hydrological variations were also evaluated in space to asses the effect of the smaller dams built on the Hungarian section of the river.

2.2. Geoinformatical analyses

Morphological changes were evaluated on the basis of maps (1883, 1937, 1957, 1972 and 1985), aerial photographs (1953, 1966, 1975, 1988, 1997 and 2002) and satellite images (2007). All resources were geo-corrected by applying the Hungarian national co-ordinate-system (EOV). The horizontal channel parameters which reflect the morphological metamorphosis of the river were measured and their temporal changes were evaluated. The determination of these parameters was based on the digitised bank-lines.

2.3 Analyses of short-term bank erosion

The rate and pattern of the active bank erosion over a 2.5-year period were observed by field surveys using Sokkia SET310 total station and geodesic GPS. The location of the eroding bank line of 8 meanders was surveyed 4 times within 2.5 years (28-29.03.2008; 20-21.08.2008, 26-27.08.2009 and 05-07.08.2010). The measured points were transformed into the national co-ordinate system (EOV) using GPS data. The average rate of bank erosion was calculated in m/half year, because that was the minimum recurrence interval between the surveys. The observed erosional rates and the hydrography of the studied periods were compared to assess the effect of different stages and extreme hydrological events on bank erosion.

Grain-size distribution, vegetation and height of the banks were also surveyed to evaluate the erodibility of the bank. Grain-size distribution analysis was carried out by corings, sampling the bank material at meander apices, ca. 1-2 meters from the bank-line. The sampling-depth was the actual low water-level and samples were taken from every 10 cm. The grain size distribution of the sandy-gravely samples was measured by wet sieving.

2.4. *Analyses of point-bar development*

The date and rate of the point-bar development within the last decades were calculated by dendro-geomorphological analyses. The age of willow and poplar trees were measured along cross-sections. These pioneer species were sampled because they determine the age of the point-bar surface accurately, thus they indicate exactly those floods which deposited the material of the new point-bars. The age of the cored samples were determined on a Lintab dendrological measurement desk.

3. Results

3.1. Long-term alteration of the hydrological regime

3.1.1. The hydrological regime is the most important variable controlling meander development. Therefore, its significant changes were revealed for the entire 20th century. Hydrological parameters did not change significantly until the late 1950's (1956–1957), they reflected stable and equilibrium conditions. From the late 1950's until 1997 significant changes were detected in hydrological parameters: the duration of discharges over mean discharge decreased (from 33.6 % to 21.5%), but that of the low discharges increased; water stages dropped, but extremities increased.

3.1.2. The degree of change in water stage and discharge were not similar. Water stages belonging to low discharges decreased between 1960 and 2009, reflecting channel incision. On the other hand water stages related to higher discharges (above 200 cm) increased, indicating the decrease in channel cross-sectional area since 1960.

3.1.3. Since the late 1990's the hydrological parameters seem to return to the values experienced in the 1950's. The duration of effective and mean discharges increased. However, during the last 10 years the extremities in water stages increased further: the height of peak stage exceeded the previous maximum water-level on record in 2006 (434 cm) and then in 2010 (503 cm). (Furthermore in 2010 two extreme floods occurred within one month!)

3.1.4. The annual water regime also changed considerably. Low-water periods extended to the winter months, consequently the rate of bank collapse increased due to the freeze-action. In contrary, floods in the summer became more frequent and higher, resulting accelerated channel development.

3.1.5. Such modifications in the regime are not unique in Hungary, as similar processes were observed on the River Maros. The most important changes were observed in the yearly low-water level. The yearly low-water stages increased until the 1970's; however they decreased radically afterwards (*Sipos* 2006). It was never below -50 cm between 1940 and 1981 (at Makó gauging station), but after 1981 it varied between -50 cm and -104 cm (*Kiss and Sipos* 2007).

3.1.6. The alteration of hydrology on both rivers was probably is in connection with changes in the rainfall and run-off pattern on the catchments. The exact causes of these changes have not been identified yet, but they are probably in connection with climate-change (extreme precipitation) and with human interventions (increased water storage and water extraction). As these natural and anthropogenic factors might affect the river system in the same way; they can superimpose on each other.

3.1.7. Considerable alterations in the hydrological regime are the main causes of river metamorphosis, which is clearly indicated by the changes of morphometric parameters (e.g. width, sinuosity, cross-sectional area) after the 1950's.

3.2. The effect of the altered regime on meander development

3.2.1. As a result of hydrological changes channel morphology has also changed on the River Hernád. The channel incised, which was indicated by decreasing water stages at low discharges. As a consequence former point-bars got to a relatively elevated position, above the height of mean discharge, and their surface could be stabilised by riparian vegetation. Incision and simultaneous point-bar stabilisation resulted in intensive channel narrowing and the decrease of cross-sectional area. In 1953 the maximum and minimum width of the channel varied within a great range, the channel width was the greatest at the apices of bends, thus large point-bar surfaces formed. Since then the channel width decreased significantly due to the altered hydrology. The highest rate of the width reduction took place between 1966 and 1975, when ca. 30 % reduction was measured at all sites. By 2002 width conditions became more homogenous.

3.2.2. Correspondingly, on the River Maros channel width varied within a great range as well (from 87 m to 137 m) in 1953. However, in the last 50 years considerable width reduction was measured simultaneously with the decrease of low-water stages. The most intensive narrowing (28 %) occurred between 1953 and 1964, since then the narrowing is continuous, but at a smaller rate.

3.2.3. As an answer to the hydrological disequilibrium the meander pattern of the River Maros has also changed. This was revealed by the reduction of chord lengths and meander lengths while amplitude remained constant on the unregulated section of the river.

3.2.4. On the River Hernád the meander metamorphosis as a response to hydrological disequilibrium was unequal at bends with different size. On large meanders secondary bends developed between 1953 and 1975, which became independent small meanders by 1988. Consequently morphometric parameters also altered, as the chord length, meander length and amplitude decreased. According to *Hooke and Harvey* (1983) the development of secondary bends is usually a consequence of meander growth, however on the River Hernád the development of secondary bends occurred simultaneously (1975-1988) following the construction of the greatest Slovakian dam. Thus the transformation of original meanders was likely a response to hydrological changes – caused by human stress, and not an answer to an individual event driven by natural sinuosity changes. Between 1998 and 2002 the amplitude of the new bends became larger but the chord length remained constant.

In contrary the changes of the smaller meanders were less significant, as their amplitude and meander length increased just slightly, indicating meander growth. It suggests, that the small meanders developed "normally" despite of the altered hydrological conditions.

3.2.5. Since the late 1990's the hydrological parameters seemed to return to the values of the 1950's and 1960's. The duration of effective and mean discharge increased. However, the meandering pattern could not absorb these changes quickly, as no pattern change was detected until 2007. However, the narrow and small bends slow down the flood waves, therefore the height and duration of peak stages can increase, raising flood hazard. This could be observed in the last years, when peak flood levels reached new records in 2006 (peak stage 434 cm) and in 2010 (503 cm).

3.3. Spatial changes of environmental variables

Beside the temporal modification of morphology significant spatial differences were detected on the River Hernád. The studied reach and their sections show different meander development-rate and pattern. The greatest differences were measured on the meanders of the Alsódobsza section. This variety is likely caused by the spatial changes in environmental variables.

3.3.1. Reach scale control Slope as an environmental variable affecting longer reaches

3.3.1.1. The spatial alteration of slope causes considerable modifications in the meander pattern on the River Hernád between Szentistvánbaksa and Gesztely, where the different rate of up-lift between several fault lines influences the slope. On this reach sections with highly different sinuosity, meander belt width, meander migration rate and pattern could be identified in accordance with the alteration of slope. Sinuosity, meander length, and meander belt width increased in order to balance eliminate the increased gradient.

3.3.1.2. This spatial alteration of the slope is probably the consequence of the neo-tectonic movements, as in the Hernád-valley the rate of vertical uplift is 2.3 mm/y (*Joó* 1998). The tectonic origin of these pattern changes is indicated by the spatial boundaries of the sections, as they are at same place on each date (1883-2007).

3.3.2. Escarpment as an environmental variable affecting shorter reaches

3.3.2.1. The development of the meanders shifting eastward is controlled by an escarpment running along the river. The effect of escarpment on meander development was studied on several sections of the River Hernád between Szentistvánbaksa and Gesztely. The lateral migration rate of these meanders slowed down exceedingly as they got close to the escarpment. The migration rate is inversely proportional to escarpment height. Two characteristic patterns of meander migration was found in this situations: either the apex of the meanders flattens and lobes (compound meanders) appear, or asymmetrical meanders develop.

3.3.2.2. The radius of these asymmetrical meanders decreased continuously (e.g. the radius of a meander near Sóstófalva reduced from 84 m to 76 m between 1972 and 2007) and finally natural meander cut-offs occurred. Thus, meander cut-offs are more frequent in cases when meanders encounter with the escarpment.

3.3.3. Meander scale control Local environmental variables affecting individual meanders

3.3.3.1. The rate of bank erosion differs significantly even on a short section of a river, suggesting that local boundary conditions (e.g. bank material, vegetation) control the rate of meander development on a meander-scale. The medium sand (0,32-0,64 mm) content of the bank material is in the strongest relation with the horizontal bank erosion rate. Thus the short- or long-term rate of bank erosion is directly proportional to the medium sand content of the bank at the toe. Eroded banks at the studied meanders were always covered by grassland, thus the role of vegetation as a control variable could not be examined.

3.3.3.2. Considerable temporal difference was detected in bank erosion rate, suggesting that the stage and pattern of meander development also affect the rate of bank erosion. At low sinuosity meanders (under 1.4) the bank erosion rate was inversely proportional to sinuosity. However at higher sinuosity other morphological parameters also affect bank erosion rate – e.g. the relationship with neighbouring meanders.

3.4. *The effect of direct engineering works on meander development*

3.4.1. The dams on the Hungarian section of the River Hernád produce negligible alteration on the water regime, as they are fairly small. The main effect was that the extremities of water regime slightly decreased towards the Gesztely gauging-station. During long-lasting low-water periods water stages were slightly higher here than at Hidasnémeti upstream. In turn at Gesztely the peak floods had slightly lower stages.

3.4.2. The upstream effect of dams was analysed on the Pere and Gibárt sections. The alteration of the measured morphological parameters (rate of centreline migration, meander- and chord length, channel width) was less significant, than on sections not affected by direct human interventions. The lengthening of the centreline was significantly lower (Pere: 0.9 m/y/rkm; Gibárt: 0.8 m/y/rkm) upstream of dams than on sections unaffected by impounding (Zsujta: 9.4 m/y/rkm; Alsódobsza: 6.7 m/y/rkm) and its rate decreased towards the dams. The variability of channel width was also smaller and it decreased toward the dams. On the impounded sections the morphometric parameters of single meanders changed similarly to those unaffected by human interventions, however the degree of these changes were smaller. Even on the impounded sections substantial transformation can occur during floods, as three meanders were naturally cut off on the Pere reach since 1937.

3.4.3. The effects of bank revetment were investigated on the Gibárt section on River Hernád and in a meander near Ferencszállás on the River Maros. On the Gibárt section the increase of centreline length was rapid (1966-1975: 4.5 m/y/rkm) before the construction of the revetment. However it slowed down drastically after the intervention, as the centreline could change only on short and unregulated sections. Following river regulation works on the River Maros the modification of the meander parameters (as meander length, amplitude, channel width) arose from centreline shifting, caused primarily by the development of point-bar surfaces. The development of point-bars was enhanced by groins in the studied meander, thus intense channel narrowing took place. The rate of narrowing was 64 % in this meander since 1953, while it was just 28 % in case of unregulated meanders. The maximum rate of channel narrowing (14.6 m/y) occurred between 1953 and 1966.

3.5. The process of meander development

3.5.1. Based on the results, it can be concluded that over bank floods have considerable channel-forming effect. High rate of bank erosion was measured at all studied meanders in each periods when over bank floods occurred. For example as the result of the greatest recorded flood in 2010 the maximum bank retreat was 16.7 m/y in the most intensively developing meander. The comparison of recent and long-term data shows that the bank erosion rate in the past few years exceeded long-term values. During the last few years significant erosion occurred also during medium- and low-stage periods following the floods. The bank erosion rate even in these low stage periods exceeded the average rate of erosion of the previous 50 years. Consequently nowadays the rate of bank erosion became accelerated in comparison with the long-term average.

3.5.2. The investigation on the development of point-bar surfaces indicates that floods fairly above the bank-full stage can form point bar surfaces suitable for the colonization of the arborescent vegetation. This flood stage is above 300 cm on River Hernád (bank-full stage 225 cm), while it was 400 cm on River Maros (bank-full stage 350 cm). The most favourable condition for the stabilization of vegetation was the occurrence of low-water years following the flood on both studied rivers. However, if low-water years do not occur, the next flood can destroy the vegetated point-bar surfaces, as the seedlings are not strong enough to resist the flood and to protect the surface from erosion.

3.6. The dynamics of horizontal channel changes

3.6.1. Point-bars develop at an irregular rate during high-level floods and subsequent low-water years, while bank erosion on the concave banks is more or less continuous, its rate depends on water regime.

3.6.2. As a consequence of the above described processes, channel width changes cyclically: Due to the lateral erosion the channel widens and it creates favourable conditions for the formation of great point-bar surfaces. This process is more pronounced if floods return frequently enhancing bank erosion and the stabilization of the vegetation is limited. However, if years characterised by mainly low-water stages occur the woody vegetation can stabilize the point-bar surfaces and this leads to channel narrowing. Accordingly, channel width is controlled by the magnitude and frequency of floods and the duration of low water periods.

3.6.3. Based on the results, it become apparent, that the modification in the water regime generates drastic metamorphosis in the river, as the channel adjusts to the new hydrological conditions. The highly (and almost freely) migrating River Hernád can absorb these modified hydrological conditions within few years by altering the horizontal meander parameters.

3.6.4. Since 1990 the change in characteristic stages and frequency of floods highly influence the long-term tendencies of channel migration. The higher rate of bank erosion contributes to an increased sediment discharge, supposedly leading to a more intensive development of bed forms.

3.6.5. In the long run the general decrease in discharge initiates channel narrowing. In addition meanders reach their maximum sustainable length at the given discharge. As this threshold is exceeded by the decrease of discharge, new riffles and secondary bends develop. At the same time the channel width increases slightly in the apices of the new secondary bends. If the discharge decreases further channel narrowing continues and new, even smaller, tertiary meanders develop on secondary bends. Meanwhile the cross-sectional area of the channel also decreases. With the means of this process the river will adjust the channel to the new hydrological conditions, and reaches an equilibrium stage. However, if the discharge increases again (as it happened in the last decade), the chord of the secondary meanders will grow due to the intensive lateral erosion. If the increased discharge will be maintained for long enough, the meander pattern will be adjusted to this variable, thus the original pattern will develop.

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