MORPHOMETRIC CHANGES OF THE RIVER BODROG FROM THE LATE 18TH CENTURY TO 2006

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Abstract
The river regulations of the 19th century have affected each of our rivers to a different degree. In the case of the River Bodrog it was stronger than the average. In our paper a section of the river between Bodroghalász and Szegi was examined, the extent and intensity of river channel changes was intended to be determined. The applied series of maps and aerial photos was georeferred and the river channel was vectorized. The morphometric parameters of the channel were measured and the changes were evaluated using the created database. From methodological aspect we concluded that the 9 variables can be grouped into 3 factors therefore most of the indexes can be substituted. We measured the changes of length and lateral shift of the channel using GIS methods. Three development periods were identified based on our results. In the first period the development of the river was characterized by natural processes. Then, the development of the river altered owing to the antropogenic impacts. In this transient phase the average shifting of the channel was 7.43 m/y. In the third term this value reduces to 0.2 m/y as the river is getting to reach the equilibrium stage.

Keywords: river regulation, GIS, channel morphometry, channel development

1. Introduction

The smaller or greater change of the morphological parameters of rivers is a natural phenomenon, but human activity may accelerate or hinder certain processes. The channel development was drastically altered by river regulations beginning with the 19th century. Due to this process the morphology of the Hungarian rivers changed artificially more or less. On smaller rivers the interventions were not so drastic (e.g. the River Hernád); in the cases of these rivers natural processes (e. g. the natural cut-offs) are still important similarly to the natural state (Laczay, 1977; Blanka and Kiss, 2008; Blanka, 2009). Regarding the other rivers the regulations have drastically changed the natural improvement of the river channel (Sipos and Kiss, 2001, 2004; Fiala et al. 2005, 2006a, 2006b; Kiss and Sipos, 2003, 2008). A good example for the latest one is the River Bodrog where, in addition to the artificial cut-offs, the construction of the Tiszalök Dam has also reduced the chance of the natural developement (Laczay, 1975). As the result of these human impacts, not only the length of the Bodrog but also bank erosion processes, bank- building and -destroying activities and its morphometry have remarkably changed during (and since) the 19th century.

The aim of the paper is to trace the channel changes of the River Bodrog between Bodroghalász and Szegi based on available military and topographical maps and aerial photos. The investigations cover 222 years.

River regulation works on the 19th century.

In the 19th century extended river regulation works began in several countries. The idea of regulating the River Bodrog had already been presented in 1775. Laczay (1975) emphasised the importance of the regulation at the mouth of the River Bodrog and the River Latorca.

Later, during the mid-19th century, the Hungarian hydrological engineer, Pál Vásárhelyi also made plans for the regulation of the River Bodrog. He suggested 12 small cut-offs that were carried out in 1867. In the 1880s the two tributary streams of the River Bodrog, the Ondava and the Tapoly were also regulated. As a consequence their sediment was deposited in the Bodrog. By the end of the 1890s 15 cut-offs were created altogether, 8 of them are in Hungary. In order to controll the inland waters along the Bodrog, canals, locks and sluice valves were built. The flood controll of the Bodrogzug was completed with the building of Tiszalök Dam in 1954 (Ihrig, 1973).

In the history of the inland rivers the most powerful effect up to now was caused by the works explained above but we should mention that the natural developments can cause similar effects as well. A good example of that is the River Subansiri in India (Goswani et al. 1999). Due to an earthquake in 1950 the river channel was blocked by a big amount of substance. Following the split of the dam 3 meander loops have been cut off changing the river channel significantly. Then, the river reached its dynamically balanced state, acting upon the new circumstances.

2. Study area and methods

The investigation was made along a 22 km long section of the river, between Bodroghalász and Szegi (Fig.1). During the channel regulations two meanders have been cut off here shortening the course of the river and altering the channel development. Due to these works the tilting of this part of the Bodrog-channel altered from 3.5 cm to 6 cm (per km), enhancing the water flowing speed (Borsy et al. 1988).

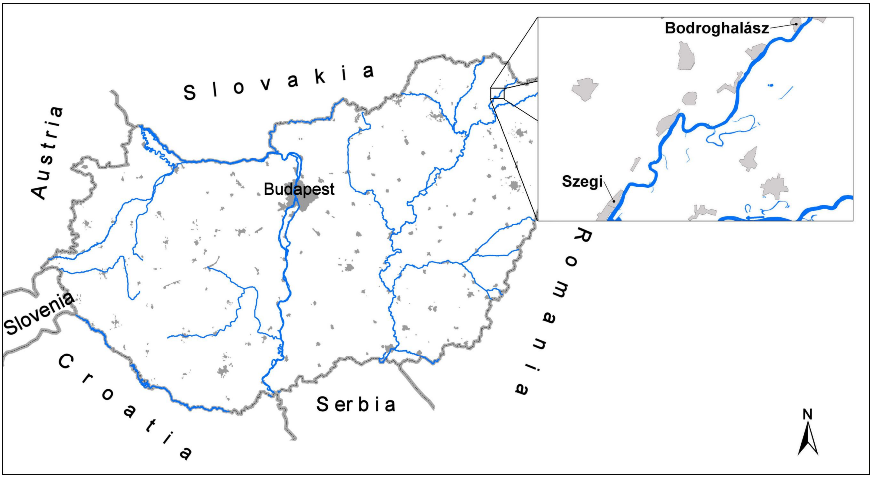

Fig. 1. The location of the examined area

In order to trace the effect of antropogenic impacts we tried to collect data and map sources before and after the main regulation events to compare them. The First Military Survey (1763-1787) was the first topographical survey in Hungary which provided detailed and regular information about the whole area. The map depicts the river in its natural state before the great river-regulations. The sections covering the study area were accomplished in 1783-1784. The accuracy of the map is basically worse than the other maps used in our enquiry owing to the unsophisticated methods applied during the survey and the lack of an unified projection system. Therefore, the calculated parameters from this map are only quasi- informative, however, we consider it as crucial data because it is the oldest map- sequence of the River Bodrog.

The Second Military Survey of this area took place in 1857 (yet before the first main regulations started). The survey measurement had substantially higher accuracy requirements (application of optical tools) and unified projection (Nagy, 1985). Both military survey maps mentioned above are available in digital format but it is practical to repeat the projection- transformation on the study area.

The next map (scale 1:25000) was made in 1930 by the Bodrogközi Tiszaszabályozó Társulat (Association of the River Tisza Regulation) (Fig. 2) in order to map the inland water controlling.

Another 1:25000 topographical map of the Bodrog was made in 1975. This was made with the help of map generalizing – originating from the Water Resources Research Centre (VITUKI) – which were originally the size of 1:10000.

Fig. 2. A detail of a map of the Bodrogköz from 1930

In addition to the maps, aerial photos played a crucial role in the research. Other authors have made similar studies based on snapshots taken in space: for example Xiaojun et al. (1999) used 19 databases to analyse the changes of the river channel of the Yellow River in China. The aerial photos of 1952 and 1988 were taken by the Military Institute. The last aerial photo of the area was taken in 2006.

Table 1. Methodology: sources and anthropogenic impacts

Mapping, aerial photos, satellite images	Anthropogenic impact (regulations)
1784, 1850	
	1867, 1880, 1890
1930, 1952	
	1954
1975, 1988, 2006	

3. Database processing

Since the study area can be considered nearly flat, we applied simple "ground control points transformation" in every case in ArcGIS 9.0 software. The transformational polynoms were of second degree and we used the nearest neighbour method with the maps and that of the cubical convolution with the photos.

In the next step the river channel was vectorised in ArcGIS 9.0 and some projection lines (e.g. boundary lines) were constructed in order to support the measurement of certain parameters. Then, the following parameters were measured: the chord which is the distance between two neighbouring inflexional points (intersection of the thalweg and the center-line); the height of the meander which was defined as the greatest perpendicular distance between the the chord and the center line; the length of arch which is the distance between two inflexional points along the line of current (thalweg); and the radius of curvature which was defined as the radius of circle fitted into the meander bend (Fig. 3) (Félegyházi et al. 2006). These indexes were calculated for every existing meander in every time horizon thus creating a database of 9 variables.

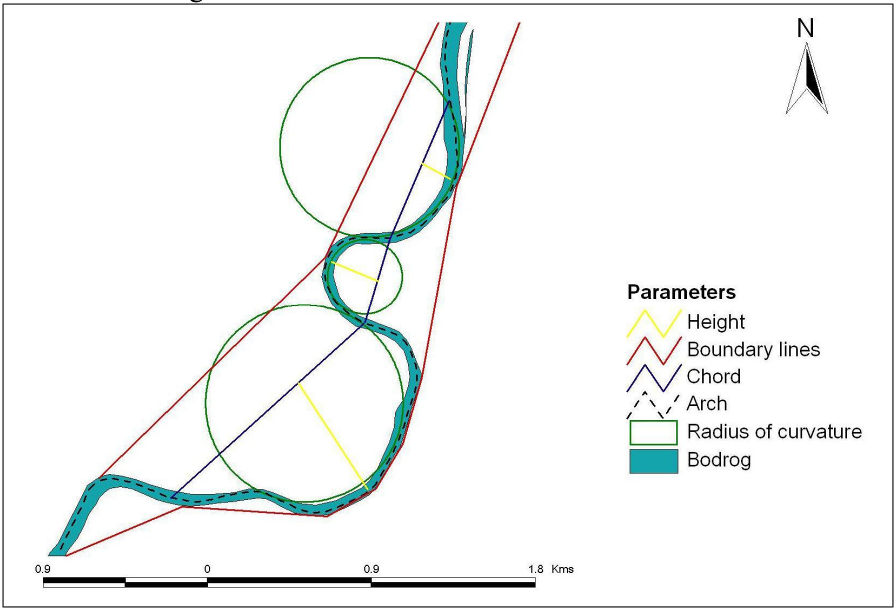

Fig. 3. The measured parameters based on the database of 1952

In order to study the river channel development (development index of stream of the river), the distance between 2-2 centre lines were measured at every 500 meters along the reach, at different time thus we got six set of database (due to the seven centre lines). We measured the change in the length of the selected section and the lateral migration of meanders. During the statistical analysis of the lateral meander migration, the database mean, the upper and lower quartile and median of the datasets were evaluated (see Fig. 6). We subtracted the straight distance between the starting point and the endpoint from the actual length of the river channel, so we got the rate of the developement index of the river stream (Félegyházi et al. 2006).

In order to measure the connections among the variables of the database a correlation matrix of the indexes were created, where all data on the meanders from every time horizon was used. Since the data did not show normal distribution even after normalisation with the $y=log(x+1)$ equation, Spearman rank correlation and principle component analysis (PCA) were carried out.

Table 2. Variables applied in the database

Variable	Description
h - chord	length of line between 2 inflexion points
m - height of meander	length of line perpendicular to the chord
i - length of meander	measured between 2 inflexion points
R - radius of meanders	radius of circle fitted into the meander bend
ß – i/h	development type of meander according to Laczay (1982)
meander maturity (Schoklitsch 1930)	comparing half-circle drawn on chord to meander length
meander complexity (Brice 1974)	9 type of meander phases
meanderwandering potential (Hickin, 1974)	based on: R/width

4. Results

4.1. Evaluation of the applied variables

The values of the parameters were measured and assigned to every riverbend in every time horizon creating a database containing nearly 900 data. The investigation of the data proved that multicollinearity exists between the variables, that means interdependency and a possibility for data/variable reduction (Table 3). The PCA (Varimax rotation, KMO=0.55) confirmed our suspicion that the indexes can substitute each other. The 9 variables were grouped into 3 factors. The first factor (51% of the variance) included the Schoklitsch and Laczay indexes referring to the stages of meander development together with m, ß and γ. The complex index of meander-wandering (R/w) was grouped in the 2nd factor with R, i and h (45% of variance). The classification based on Brice was grouped alone (Table 4) explaining 4% of the variance. The value is quite low, however, this index is used in the US engineering geology. Further investigations are needed to check the persistence of the component structure, we may advise to apply 3 of the 9 variables: R/w, Brice's index and ß, 2 of which has already been adviced by Timár (2005) as well.

Table 3. Spearman rank correlation of the applied variables (bold values: $p<0.05$)

Variables	h	i	m	R	ß	γ	R/w	Laczay	Schoklitsch	Brice
h	-	**0.63**	0.21	**0.92**	-0.47	**-0.62**	**0.84**	-0.41	-0.47	-0.05
i		-	**0.83**	0.50	0.28	0.08	0.48	0.25	0.14	0.02
m			-	0.06	**0.70**	**0.55**	0.09	**0.67**	0.54	-0.01
R				-	-0.55	**-0.71**	**0.94**	-0.47	-0.50	-0.14
ß					-	**0.94**	-0.46	**0.91**	0.82	0.07
γ						-	**-0.64**	**0.88**	**0.82**	0.04
R/w							-	-0.37	-0.44	-0.11
Laczay								-	**0.89**	0.04
Schoklitsch									-	-0.03
Brice										-

Table 4. Rotated Component Matrix(a)

	Component		
	1	2	3
h	-.222	**.963**	-.024
i	.328	**.929**	.007
m	**.790**	.548	.038
R	-.272	**.939**	-.075
ß	**.934**	-.117	.070
γ	**.931**	-.189	.065
R/w	-.230	**.916**	-.055
Laczay	**.888**	-.069	.062
Schoklitsch	**.838**	-.225	-.063
Brice	.060	-.067	**.994**
Explained variance	51%	45%	4%

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.
Rotation converged in 4 iterations.

Complex morphometric indexes like Laczay's or Schoklitsch's can be abandoned and simpler attributes (like m) can be attached to each bend. The results mean that two major river features should be concerned in the further examinations: the aggradation of meanders (R, i, R/w) reflects the changes of length (4.2), while variable m grouped into the first factor refers to lateral shift (4.3). The third factor reflects to the development stage of the riverbed. The first two of these factors (responsible for 96% of the variance) are investigated below in the article since they characterize the processes best.

4.2. Measuring the changes in length of the section (1784-2006)

The river regulations of the 19th century caused drastic changes on the River Bodrog since it altered the natural river channel (Fig. 4). The pattern of the river changed due to the cut-offs and the increase in the middle course.

At the time of the First Military Survey (1784) the studied section of the River Bodrog was 34,290 m long reflecting natural conditions (Fig. 5). By the Second Military Survey (1857) the river became longer by 4 km (11% increase in length). The growth of the length and the development of the meander-bends were caused by the meander-formation. The channel regulation of the Bodrog began in the 1860s, therefore the two data mentioned above refer to the speed of natural processes meaning a 55 m/y lenghtening of the course of the river. On the studied reach two well-developed meanders were cut off until 1884. These were large meander bends, therefore the examined section of the river became shorter by 15.8 km decreasing the lenght by almost 40% between 1857 and 1930.

In the following 22 years (1930 - 1952) the river became longer with 770 m (35 m/y increase, 3.5 %). Consequently the river leant to its hydrodynamic balance, which began with the growth of the remained meanders. This is the result of the increased velocity connected to slope of the water (Fiala et al. 2006), however, due to the regulations the speed of increase in length remained moderate compared to 1784-1850 (55 m vs 35 m). The growth of the meanders can be evaluated based on the length of arch (i), since their mean value has grown by 7 % between 1930 and 1952.

Since 1952 a gradual decrease of course length can be detected. At this time the river has tended towards reaching its dynamic equlibrium. Between 1952 and 1975 the river became shorter by 50 m. That means 2.1 m/y shortening. Between 1975 and 1988 the river shortened by 6 m (0.46 m/y), later by 4 m in 2006 (0.22 m/y) (Fig. 5). It is important to state that not only natural but antropogenic effects can also resulted in shortening. Separating them is very complicated since there is not any exact information about the antropogenic works on this section of Bodrog.

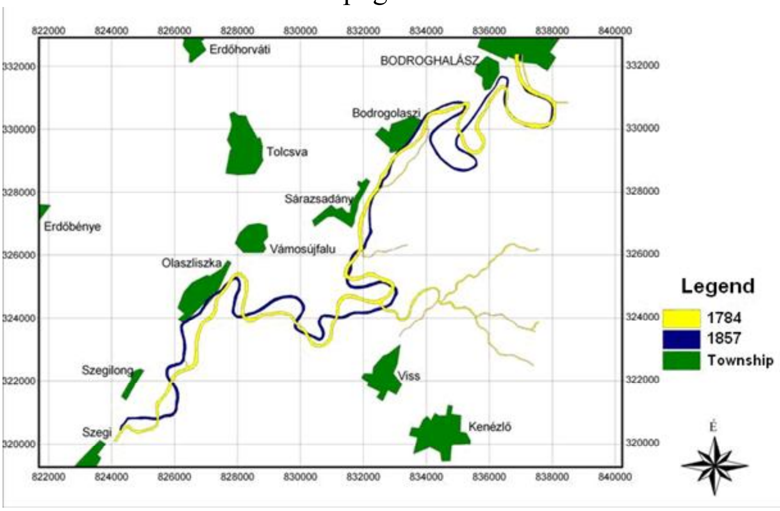

Fig. 4. The study area at the time of the First (1784) and Second Military Survey (1857)

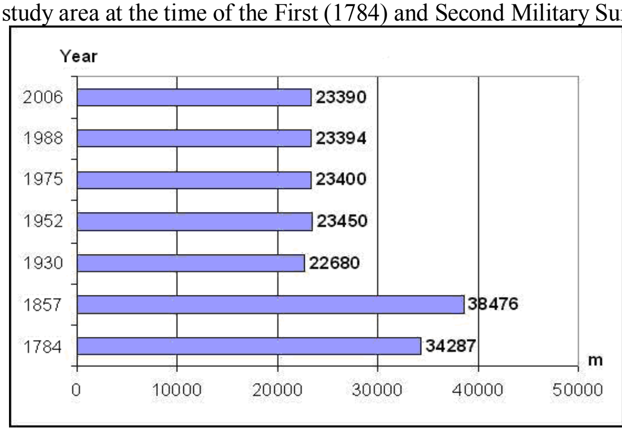

Fig. 5. The length changes of the studied reach of the River Bodrog between 1784 and 2006

4.3. Measuring lateral migration

The degree of lateral migration was measured by the shift of center-line (Fig. 6, Table 5). Comparing the First and the Second Military Survey, the lateral migration of the 500 m sections shows great variability (~210 m – 2.88 m/y). The mean rate of lateral shift is (regarding these sections) 195 m (2.67 m/y), the middle half of the data varies between 52-302 m. On the one hand, the distances have grown notably in the second period (1857-1930) and on the other hand, they show a wider spectrum than before. This is caused by the regulation-work of the 1880s when the course of the river was transformed. This explains that the 50% of the data falls between 118-1006 m, and that the upper-quartile is over 2000 m. The annual rate of lateral shift also exceeded that of the former period, which means that the decrease in length resulted in increasing lateral movement. Between 1930 and 1952 the river started to regain its dynamic balance so the data spectrum will show lower migration rates (~10 m – 0.45 m/y). After this, there were no sigificant changes, probably due to the equilibrium-like condition of the river or the regulating effect of the dam built in 1954. We have to refer to the fact again that besides the natural development of the river channel, antropogenic processes could also take place.

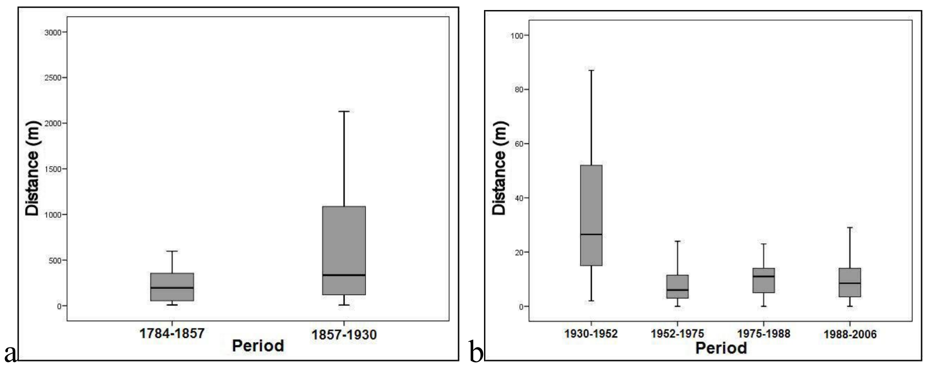

Fig. 6. Changes in the medians and quartiles (a) between the First and Second Military Survey, and (b) at the successive terms

4.4. Measuring flow-conductivity

Between the First and Second Military Survey (approx. 73 years) the value of the flood conductivity grew by 38% since the lenght of the meandering river grew more under the natural conditions. A significant decrease is observable after 1857. The sudden change was caused by the effects of the river regulation. In the next 22 years (1930-1952) the value grew by 14% from a lower rate and stagnated after 1952 (Fig. 7, Table 5).

Table 5. Annual changes in length and lateral migration of different periods

period	change in length (m/y)	average lateral migration (m/y)	flow-conductivity	characteristics	antropogenic impact
1784-1857	57	2.6	0.94	increasing length, increasing lateral shift	
1857-1930	(-238)*	3.7	1.2	decreasing length, increasing lateral shift	cutoff - increasing speed and tilting, increasing sediment transport
1930-1952	35	1.36	0.28	increasing length, decreasing lateral shift	
1952-1975	-2.1	0.45	0.32	decreasing length, decreasing lateral shift	dam construction
1975-1988	-0.46	1.1	0.31	nearly stagnating, artificial equilibrium	
1988-2006	-0.22	0.55	0.32		

* artificial

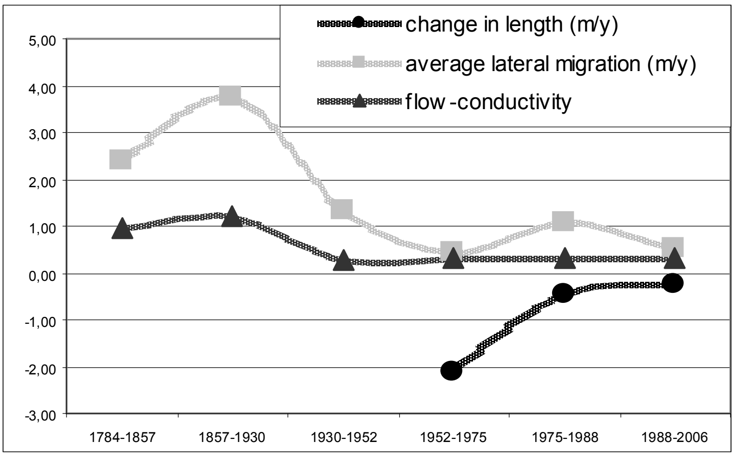

Fig. 7. The change of dynamic parameters of the river section

5. Discussion

The developement of the river in the study area can be divided into three periods. The first period represents the natural state of the River Bodrog before the regulations of the 19th century. This is characterised by increasing length and high lateral wandering. The lenght-change of the Bodrog, which was developed under natural conditions, grewn with 4 km between the two Military Surveys, as an effect of the meander formation. Simultaneously with the growth of the length, the area bounded by the cross section area boundary lines has also grown (by 1540 m^2).

The second period took place between the regulations and 1952 when the river tried to return to the equilibrium. This is confirmed by the fact that the length decrease (resulted in increasing tilting and velocity) induced accelerating lateral shift which refers to unstable circumstances. The latter can also be caused by the increasing sediment transport after the regulation of Ondava and Tapoly in the 1880s. The stream development (flood conductivity) also reached its highest rate at this time (1.2). The natural conditions were completely changed due to the regulations. The lenght of this section of the River Bodrog decreased to its 60%, and therefore the tilting (from 3.5 cm/km to 6 cm/km) – and consequently the speed – of the river has increased. Thus, the transportation capacity of the river has increased, therefore the remaining meander bends started to grow, as it is reflected by the 7 % increase in the arch lenght. Their height also increased since the river returned to its original state.

The third period was after the 1950s when the construction of the dam ended. The river continuously altered due to the changed morphological conditions and regained its state of dynamic balance from the 1950s characterised by stable conditions regarding length and lateral shift.

At the same time, with the length change the size of the cross section area and the development of the flood conductivity also changed (from 1.2 to 0.32).

The results of Blanka and Kiss (2008) show controversial tendencies on the River Hernád since the hydrologycal parameters of the stream was balanced until the 1950s, but after this the hydrologic balance was thrown out. In the case of the River Bodrog significant changes were not observed, the stream became stable as it is confirmed by the low and stagnating values of stream-conductivity, the length change and the lateral migration.

It is proven that the morphological effects of the regulations were drastic in short-run, and the anthropogenic effects had the most powerful effects in long-run as this was also stated by Winterbottom (1999). The River Bodrog adapted to the new circumstances and endeavours to reach a state of dynamic balance in its new, altered conditions.

6. Conclusions

The investigations show that GIS is an effective and exact method to record and to register an altering channel. The River Bodrog was strongly affected by the river regulations of the 19th century and the channel changed more slowly than before the river altered. The applied methods were appropriate to show the small changes as well. However, the statement mentioned above is correct only after the construction of the dam since the regulation effects were controversial. Although the length was decreased and the velocity of river increased due to the increasing tilting (which means that floods left the area earlier), the increased sediment transport caused by the increased velocity and the regulation of the upper triburaties resulted in an increasing lateral migration (Timár, 2005; Timár and Telbisz, 2005). The stages of the river development are summarised in Table 5, with the change of some of the most important indexes. We can state that the River Bodrog tends to reach the equilibrium state very slowly (but in a measurable level) after the river regulations.

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