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Quantitative analysis of the channel changes of Moldova river in the extra-Carpathian reach

PhD Dissertation Abstract

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SUMMARY

Cuvinte cheie: channel bed, braiding index, historical dynamics, millenial-scale dynamics, 14C, Moldova River

1.1 Argument

The present study makes use of the extra-Carpathian alluvial plain of Moldova river in order to address several matters which have been insufficiently tackled with in the Romanian literature, such as defining and establishing the appropriate methods to measure braided channels, the historical dynamics of the channel and the changes in the vegetation cover, as well as the millenial-scale evolution of the fluvial activity of the river based on absolute dating. By using GIS techniques we were able to undertake an elaborate string of measurements throughout the entire extra-Carpathian channel sector of Moldova river. After the analytical interpretation of the derived database we proceeded to check the resulting data in the field; thus, the lab work was constantly complemented by field work in order to validate our results.

Our approach consists of two main directions: a) the historical dynamics of the channel (based on consecutive cartographic documents) and b) the Late Holocene history of the channel (based on absolute dating). We believe that by its up-to-date research methods, valuable databases acquired and their processing according to the latest developments in the field, this doctoral dissertation has a substantial degree of originality. Moreover, some of the results have already been published, while others are in press in journals with impact factor and influence score.

Furthermore, the results obtained have additional practical value for the sustainable management of rivers (as geomorphological, geological and biological resource, or in terms of the evolution trend of the relief, etc.) and could make a significant contribution to improving the sustainable management strategies of these natural components.

1.2 Introducing the study area

The study area is represented by the extra-Carpathian sector of Moldova river (downstream of Păltinoasa village). The area of the entire river basin amounts to 4299 km^2, while the length of the extra-Carpathian sector is of approx. 110 km (table 1). The upstream limit of the investigated area is established at the exit of the river from the mountainous sector, whereas the downstream limit is the confluence with Siret river, just downstream of the city of Roman (fig.1). The general slope gradient of the river within this sector is 2,09 ‰, which commonly indicates a river characterized by strong alluvial transport activity.

Table 1 Characteristics of Moldova river and its basin in 5 gauging stations (the grey band refers to the study area)

Gauging station	River basin area Sb (km^2)	Elevation H (m)	River length (km)	Mean annual discharge (m³/s)	Suspended solid load (kg/s)
Fundu Moldovei	294	739	45	3.57	
Prisaca Dornei	567	657	94	7.30	2.44
Gura Humorului	1887	480	120	17.04	
Tupilaţi	4016	236	157	32.84	35.30
Roman	4299	180	213	35.27	16.10

1.3 Controlling factors

In terms of *geology*, Moldova river basin overlies two distinctive units, namely a mountainous unit (orogenic), which has a folded and faulted structure composed of harder rocks (metamorphic rocks) and flysch rocks, and a plateau unit (platform), respectively, which has a monocline structure consisting of softer rocks (pertaining to the molasse and platform units).

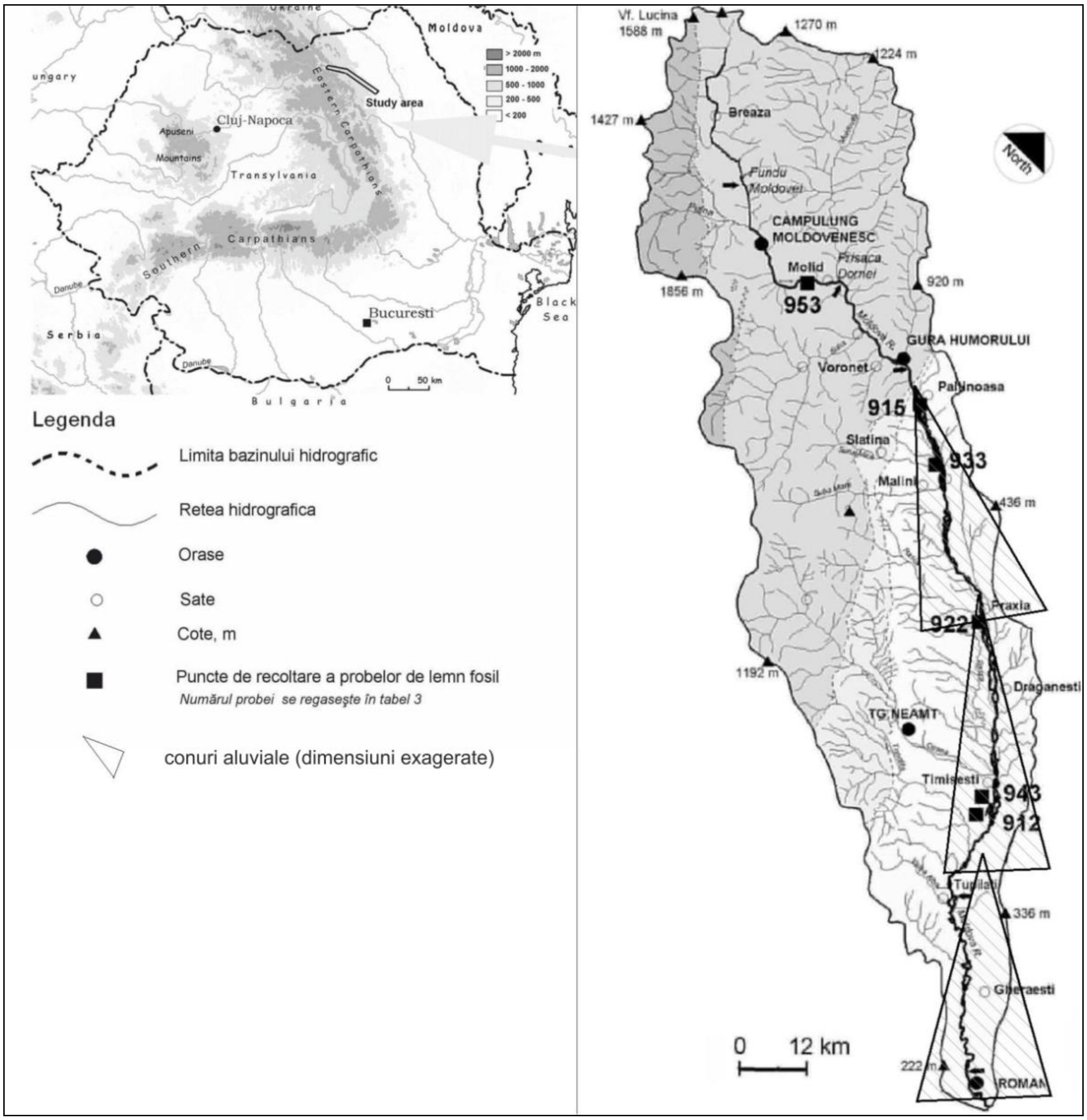

Fig. 1 Location of the study area; succesion of the „alluvial sheets" along Moldova valley

Four stages were identified in the formation of the valley and the shaping of the present state of the alluvial plain of Moldova river (pre-Quaternary and Quaternary-Holocene), of which the latter two stages (the formation of the sub-alluvial morphology and the accumulation of the alluvial complex) were of particular interest, as they represent the site and the rock where the river bed currently evolves.

In terms of *climate*, Moldova river basin falls into the *East-European climate district*, which shows some oceanic (baltic) influences within the upper basin, whereas the nuances are more markedly continental (excessive) in the lower sector of the basin. The layout of the valley along a general NW-SE direction favours the channeling of air masses due to the peculiar shape of the valley (couloir), thus fostering an *elementary valley topoclimate*.

Hydrologically, the *discharge* and the *solid load* are the factors which have the most prominent influence on the temporal and spatial dynamics of Moldova river channel. The mean multiannual discharge and solid load are shown in table 1.

Regarding the land use/cover, the forested area within the basin currently amounts to 50% (including mountain grasslands), whereas the arable land covers 27%.

The anthropogenic impact on the river bed has manifested directly through mining (of various rocks) and bank protection works, but also in an indirect manner by altering the land use/cover in the riparian zone (mining stockpiles, as well as urban waste landfills). Prior to 1989, there were 47 gravel plants in use, extracting over 1576.000 m^3 of construction rocks; the mining was diminished afterwards, but was resumed with renewed intensity after 2000.

1.4 Study protocol

The study protocol regarding the historical and millenial-scale dynamics of a braided channel follows several levels of analysis: long profile, sectors and sub-sectors, and equidistant cross sections. To this spatial partitioning we add a temporal analysis of the nature of the processes and mechanisms involved: a) styles of adjustment of the river on a historical scale – following the river dynamics over a time frame where documentary, cartographic and instrumental evidence are available (the parameters are shown in table 2); b) styles of adjustment of the river on a millenial scale – regarding the entire time frame required to build up the floodplain with an emphasis on the last 3000 years, during which we have studied the morphology and sedimentary structure of the floodplain.

Table 2 Morphometric parameters determined based on the analysis of cartographic materials (excerpt)

Morphometric variable	Manner of extraction	Aim
Channel width, *lam* (1910, 1960, 1980, 2006)	Measurements perpendicular to the channel axis, at the intersections of the floodplain cross sections with the central axis of the channel	Spatial and temporal variation in the width of the river bed bankfull Detailed multivariate analysis
Floodplain width, *laj*	Measurements perpendicular to the floodplain axis	Quantitative assessment of the river position within the floodplain; lateral displacement Multivariate analysis
River length, *lunga*	Between the intersections of the floodplain cross sections floodplain (perpendicular to the valley axis) and the central axis of the watercourse (or main channel in the case of anastomosed sectors)	Spatial and temporal variation in the river length, cumulative length of the river

Straight river length, *ldr*	Distance between 2 consecutive cross sections (in our case 100 m)	
Braiding index, *Ii*	Measurements perpendicular to the floodplain axis, to the links intersected by each cross section	Spatial and temporal variation in the braiding index
Channel migration (to the left, to the right), *Ms, Md*	Measurements on the channel migration to the left and to the right (left bank towards the left, right bank towards the right)	Spatial and temporal variation in the river banks Detailed multivariate analysis
Length of bars between 2 sections, *lo*	Measure the length of the bars (depending on the axis of each islet)	Spatial and temporal analysis of bar morphology

- *Note: each of these variables was measured each year (1910, 1960, 1980, 2006).*

The data resources consisted of maps and cartographic documents dating back to 1910, 1960, 1980 and 2005 (river channel and floodplain width, riverbank dimensions, vegetation cover dynamics, fig. 2, fig.3), hydrogeological boring data, dendrochronological measurements, absolute ages obtained by 14C dating, instrumental records from the gauging stations and data acquired by geomorphological mapping.

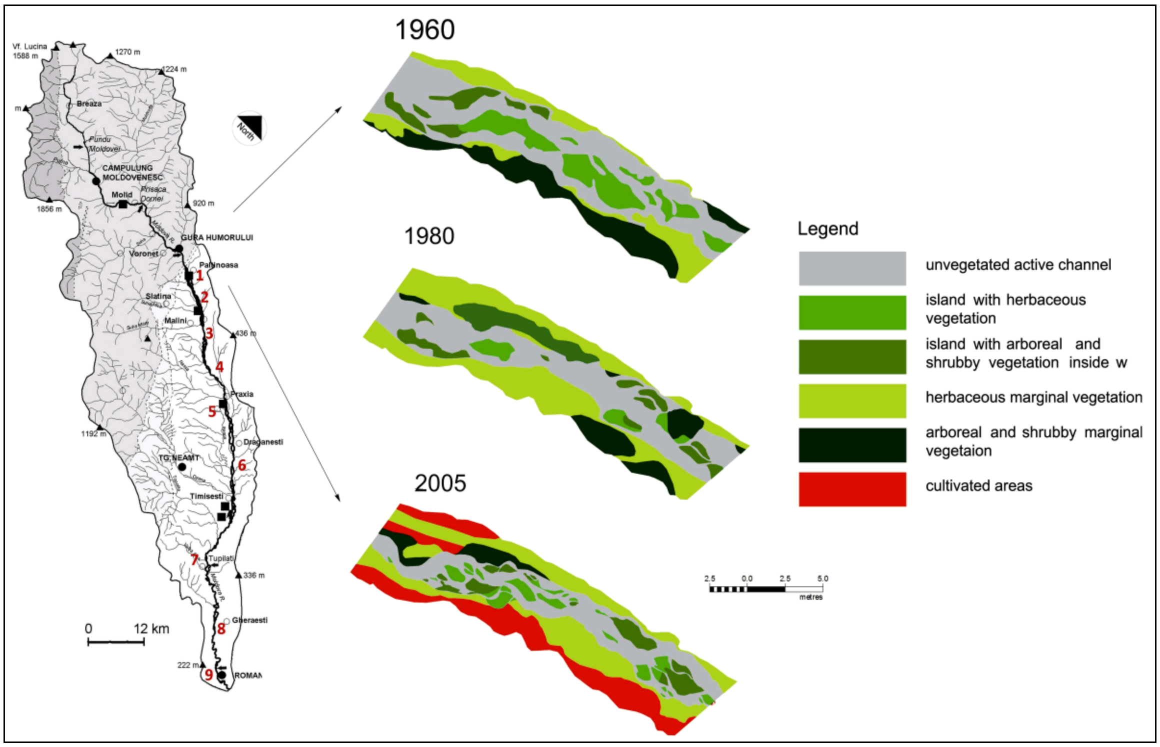

Fig. 2 Example of vegetation cover change analysis based on historical documents (Păltinoasa-Berchişeşti sector)

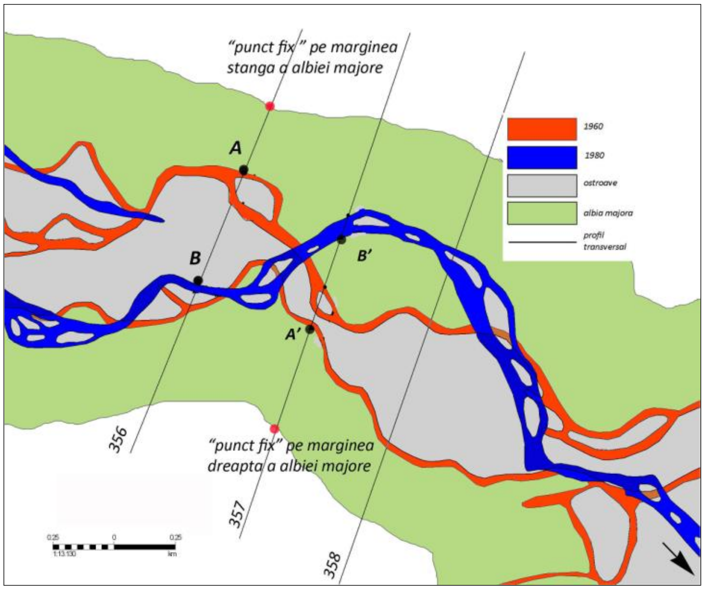

Fig. 3 Method of measuring the left - right migration of Moldova river channel

1.5 Cross section shape

The shape of the cross section (fig. 4) indicates that Moldova river falls into a category of channels with high potential for planform changes. The Lane (1935) shape coefficients computed for all the cross sections range closely within a narrow interval around the 1.00 value, hence the observation regarding the nearly perfect parabolic shape specific to braided channels.

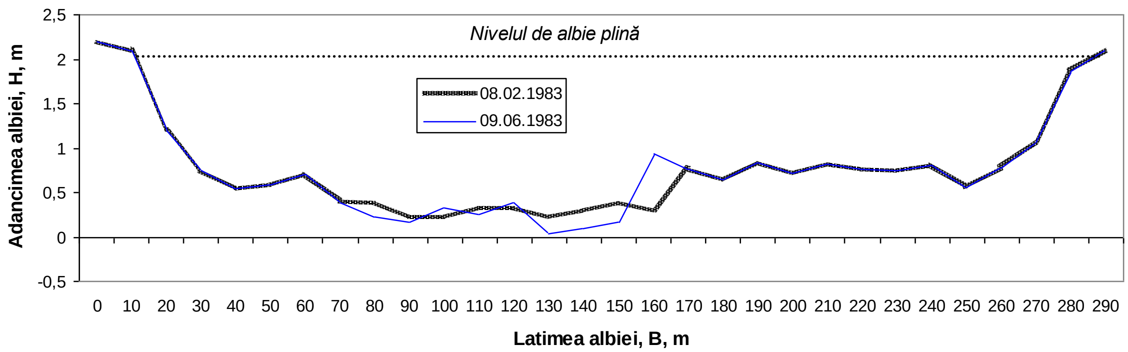

Fig. 4 Shape of the cross section of Moldova river channel in Tupilaţi gauging station (data source: S.M. Piatra Neamţ)

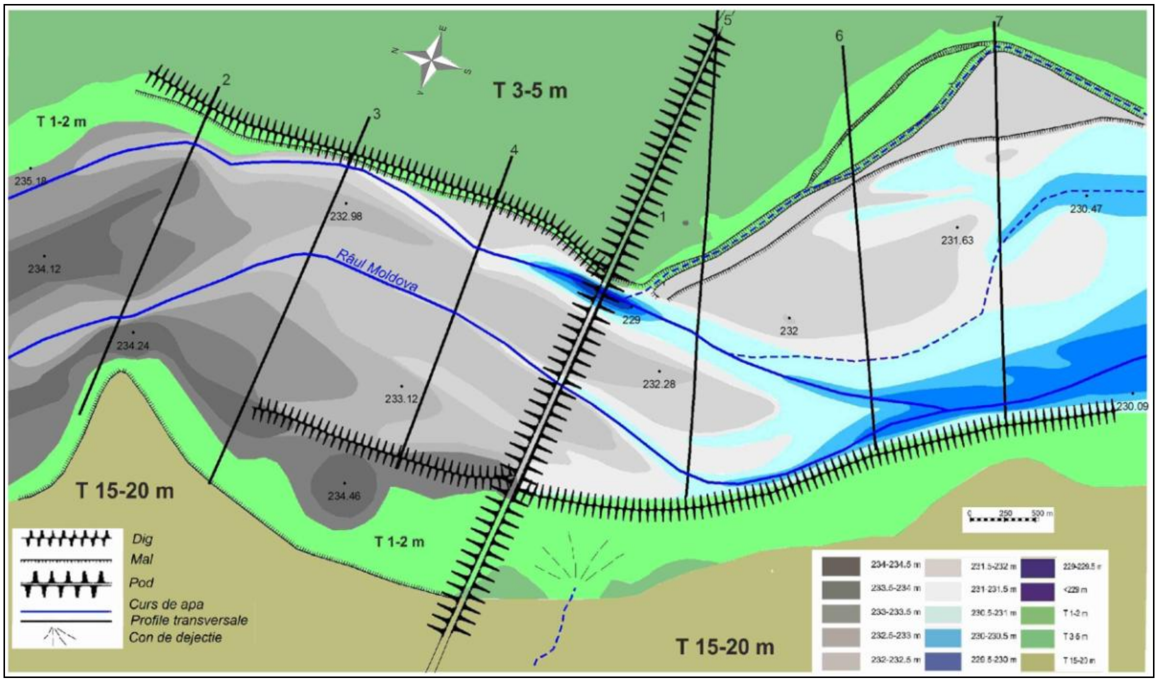

Fig. 5 Geomorphological sketch of Moldova river bed in Tupilaţi gauging station

1.6 Historical dynamics of the channel

The main results regarding the **historical dynamics of Moldova river channel** are summarized in terms of dimensional features of the channel, channel typology and rates of the alluvial processes within the entire study area, as well as the 9 sub-sectors (fig. 6).

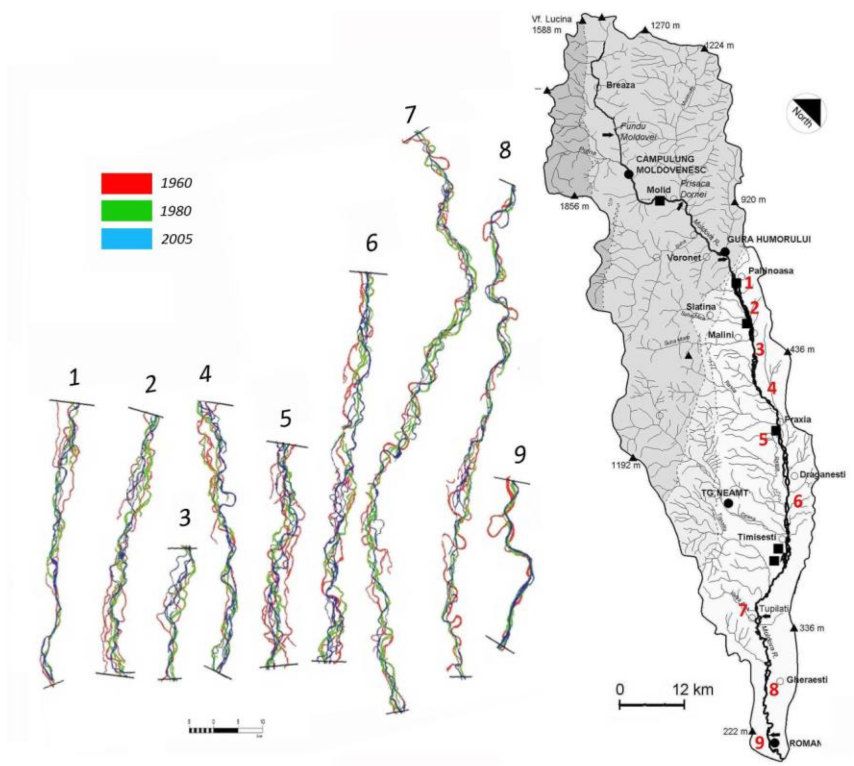

Fig. 6 Map of the channel sub-sectors along Moldova river (between Gura Humorului and Roman).

With regard to the **dimensional elements**, it was noted that:

- *the channel of Moldova river has continually grown narrower on a downward linear trend* (fig. 7), from 1219 m (in 1910) to 691 m (in 1960), 487,6 m (in 1980), to just 293,6 m (in 2005). If the channel width in 1910 is rated 100%, then the narrowing accounts for 43% in 1960, 59% in 1980 and 76% in 2005;
- *two phases have manifested in time*: the first phase - more accelerated, until 1960 (during which the narrowing of the channel occured by a rate of approx. 10.5 m/yr.), and the second phase, where the narrowing rate was approx. 8.8 m/yr.;
- along the river *the narrowing of the channel is increasingly exacerbated over the last 6 km* to the confluence with Siret river, from a maximum width of 1000 m (1910) to under 130 m (2005).

As regards the **changes in the channel typology**, quantized by the braiding and sinuosity indices, it was noted that:

- the historical trend of the *sinuosity index* shows a clear change within the last 3 sub-sectors before the confluence, where the index *increased from 1.02 to 1.18,* and this trend is propagating upstream;
- during this period, the typology of several river sectors has changed from *wandering*-braided to *wandering*-sinuous.

The relation between the channel slope and the sinuosity index indicates a marked threshold between the two types of channel, which tends to shift towards reducing the slope and increasing the sinuosity. If the rate of transfer of the coarse sediments from the river basin continues to decrease (by afforestation, sediment retention by transversal works, a.s.o.), the rate of transformation of the channel is expected to be further exacerbated. The propagation of this new type of bed occurs from downstream towards upstream.

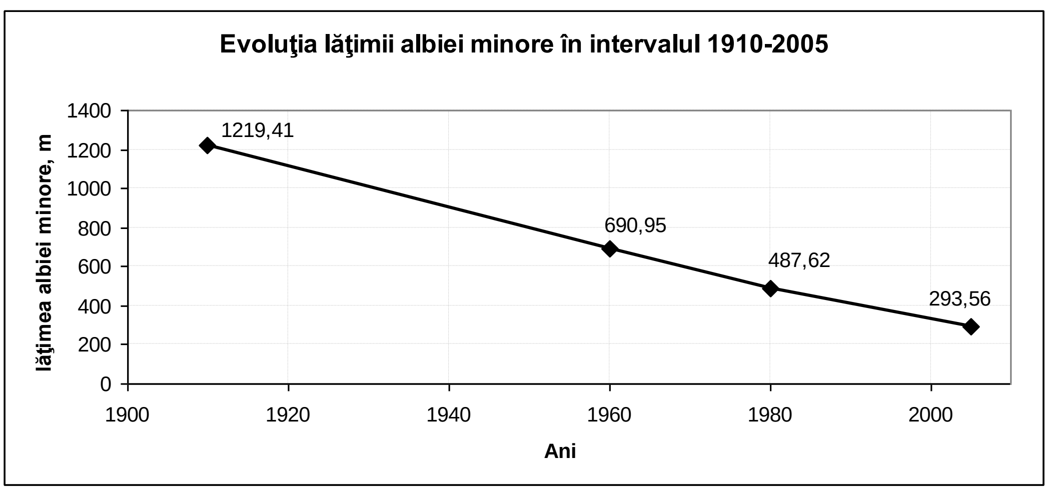

Fig. 7 General evolution of the channel width between 1910-2005, mean values for the entire study area (Gura Humorului – Roman).

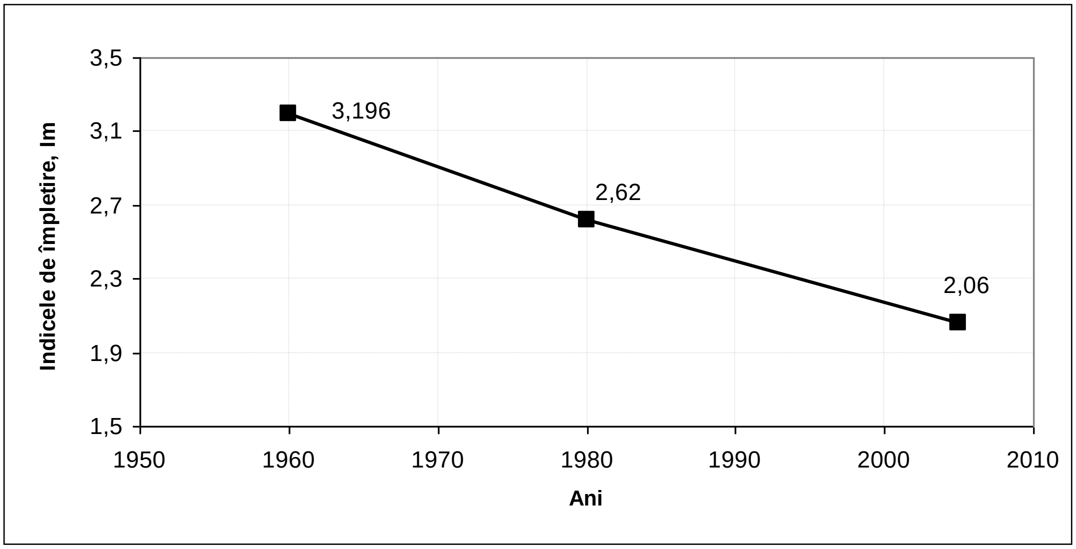

Fig. 8 Evolution of the braiding index of Moldova river between 1960-2005

- four sedimentation zones are clearly emphasized along the river, delimited by as many nodes whose location is most likely the result of the discharge input from the vigorous right-side tributaries (fig. 9). After studying their position over time, it was established that they migrated downstream over distances ranging from 105-110 m (the first sedimentation zones from upstream) to 40-45 m (the zones located downstream), which occurred simultaneously with the decrease in their amplitude.

- a single section (6.6 km long) with a sinuosity index of 1.18 was identified along Moldova river, but solely in 2005. In the previous reference years the river was either braided (1960), *wandering* (1980) or sinuous (2005). Hence the conclusion that this trend will likely expand to other sub-sectors located upstream, particularly between the main junctions.

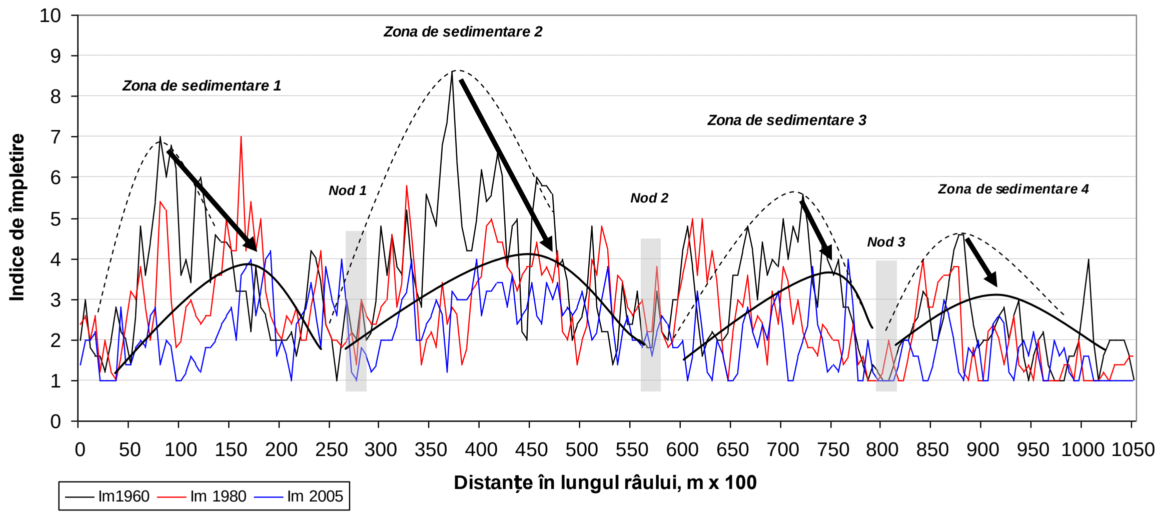

Fig. 9 Spatial-temporal variation of the braiding index in the extra-Carpathian sector of Moldova river between 1960-2005. The migration of sedimentation zones is highlighted in the chart.

Regarding the **rate of fluvial processes** (fig.10) the following trends were noted:

- the left bank, which undergoes the lowest degree of confinement in terms of limitation by the valley slopes or input from vigorous tributaries, has the highest rate of withdrawal „inwards" the active strip. The mean withdrawal rate value was 10,12 m/yr. between 1960-1980 and 6,83 m/yr. between 1980-2005;

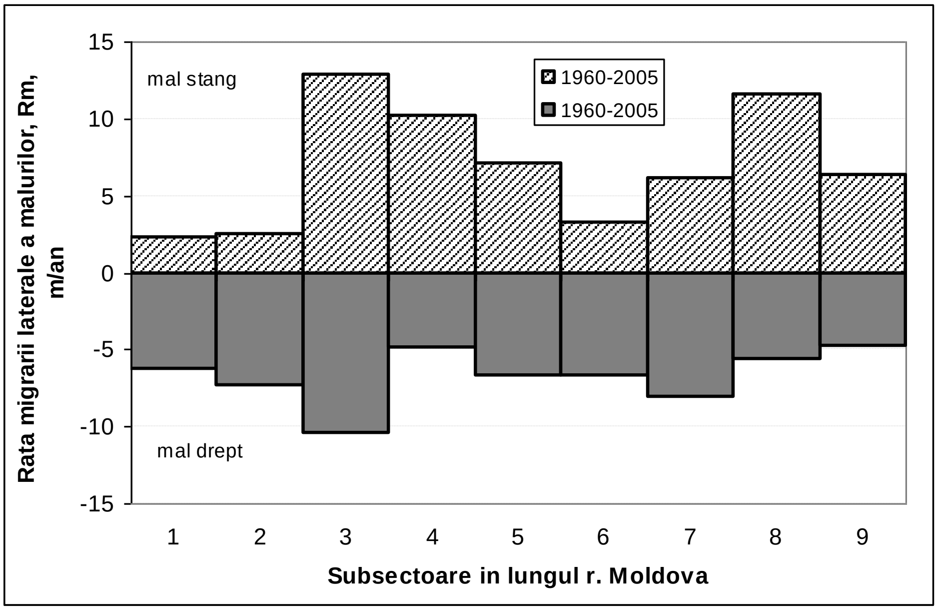

Fig. 10 The rate of lateral migration of Moldova river (mean values for the 9 sub-sectors)

- the right bank, undergoing the highest confinement and further affected by the sediment input from the right-side tributaries, has shown withdrawal rates inwards the active strip of 4,43 m/yr. between 1960-1980 and 3,55 m/yr. between 1980-2005.

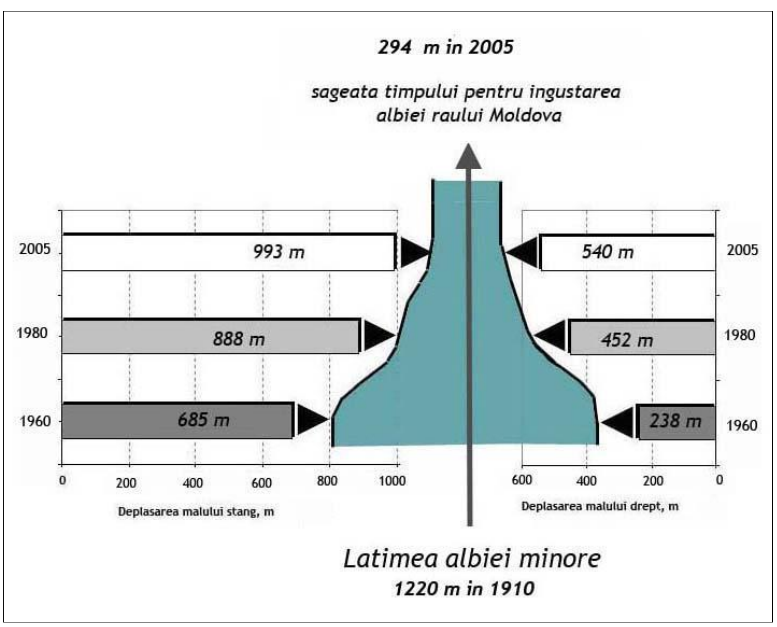

Fig. 11 Overview of the trends in the channel planform dynamics of the extra-Carpathian sector of Moldova river (Gura Humorului - Roman)

All the observations regarding the planform behavior of the channel are summarized in fig. 11, where the temporal axis of the chart shows the most marked change in the channel, namely the *narrowing from a mean width of 1220 m in 1910 to just 294 m in 2005*. This alteration occurred in the 110 km-long valley sector between Gura Humorului and Roman.

As the channel width dminished, the riparian vegetation (fig.12) (herbaceous vegetation, shrubs and trees) expanded to the terrains which were left unflooded or not undergoing fluvial processes. Thus, the area covered by riparian vegetation increased from 38% in 1960 to 71% in 2005. Vertically, the measurements performed in the gauging stations between 1960-2010 indicate continuous incision ranging from nearly 1 m in Gura Humorului to almost 3 m in Roman.

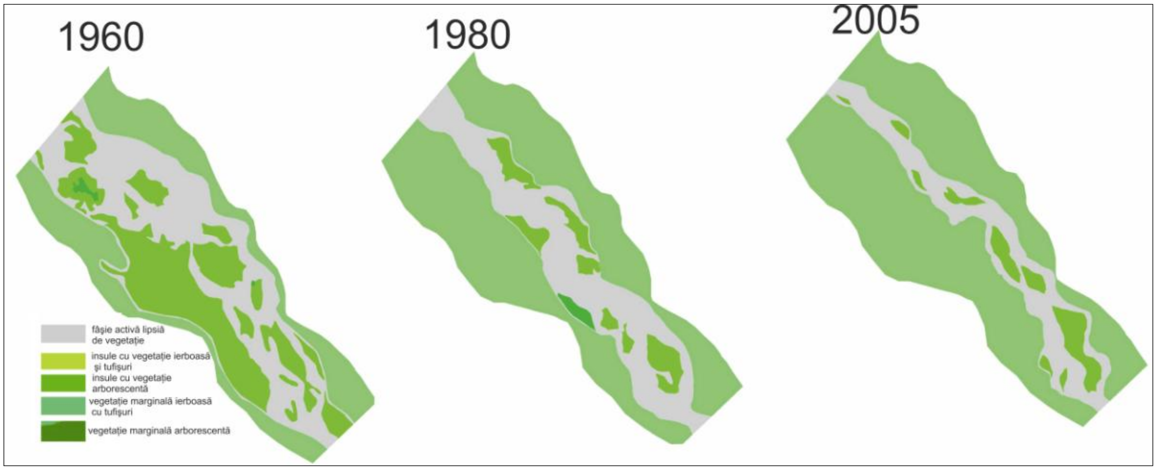

Fig. 12 Planform dynamics of the vegetation cover (sub-sector 3)

The sections located in the extra-Carpathian sector (Gura Humorului, Tupilaţi and Roman) have exhibited a consistently more dynamic behaviour over time in terms of the increasing incision along the river (fig.13). In Gura Humorului, the measurement records were only available for the 1977-2010 period, therefore the determined magnitude is possibly altered in this regard. However, the overall image of incision of the channel bed cannot be disputed. The magnitude of the incision increases from -78 cm in Gura Humorului, to -90 cm in Tupilaţi and -270 cm in Roman.

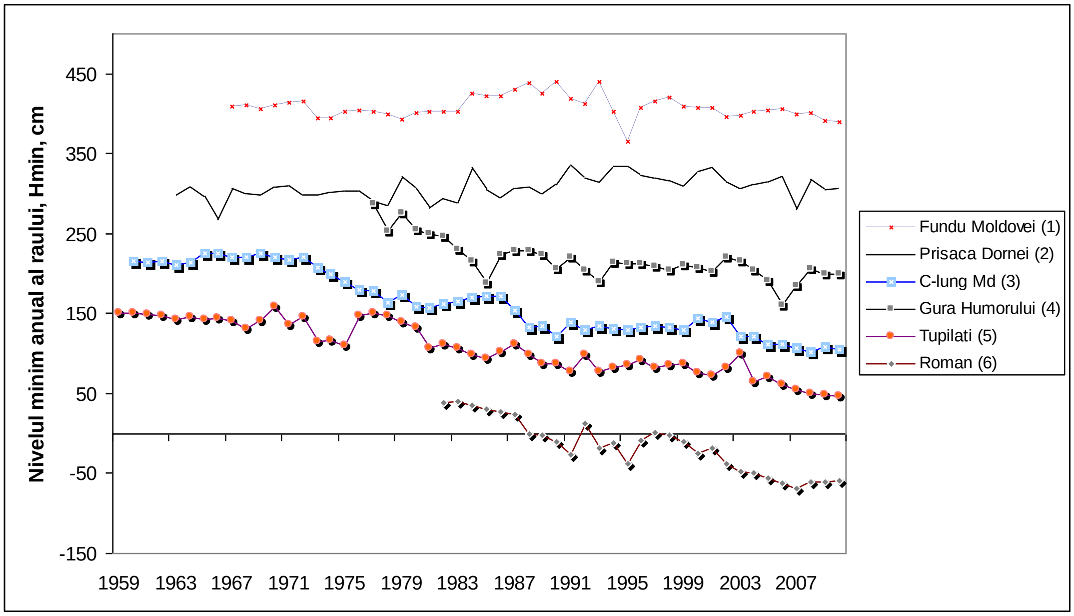

Fig. 13 Vertical dynamics of the channel bed level of Moldova river estimated based on the minimum annual level in 6 cross sections along the river

1.7 Millenial-scale dynamics of the channel

The absolute ages of the 6 fossil logs collected from the river banks of Moldova (fig. 1, fig. 14), the type of wood, the nature of the sediments, and depth where they were sampled are shown in table 3.

Table 3. The absolute ages of the fossil logs sampled along Moldova river (Chiriloaei et al., 2012)

No.	No. Lab.	Fossil wood type	Location	Sediment type	Depth (m)	Age (BP)	^{14}C calibrated age in the 68. % interval	^{14}C calibrated age in the 94.5% interval
1	Mold 953	Beech	Molid	Gravel	2	875 ± 35	1050 - 1080 cal. AD (13.2%) 1150 - 1220 cal. AD (55.0%)	910 - 840 cal. BP (26.0%) 835 – 725 cal BP (68.2%)
2	Mold 915	Beech	Bridge downstream Gura Humorului	Gravel	3	1150 ± 45	780 - 790 cal. AD (2.0%) 815 - 845 cal. AD (12.3%) 855 - 905 cal. AD (23.8%) 910 - 970 cal. AD (30.1%)	1178 – 960 cal. BP (95.4 %)
3	Mold 933	Poplar	Bridge Slatina	Gravel	3,5	650 ± 45	1285 - 1320 cal. AD (31.7%) 1350 - 1390 cal. AD (36.5%)	674 – 550 cal. BP (95.4%)
4	Mold 922	Poplar	Vadu Moldovei	Gravel	2	380 ± 45	1445 - 1525 cal. AD (48.4%) 1575 - 1585 cal. AD (2.1%) 1590 - 1620 cal. AD (17.8%)	510 – 315 cal BP (95.4%)
5	Mold 943	Oak	Timişeşti Downstream road bridge	Gravel	3	2995 ± 45	1315 - 1190 cal. BC (56.4%) 1180 - 1155 cal. BC (6.6%) 1145 - 1130 cal. BC (5.2%)	3340 – 3061 cal. BP (93.8%
6	Mold 912	Oak	Timişeşti, Downstream road bridge	Gravel	3	2005 ± 40	50 call. BC - 30 cal. AD (59.2%) 35 - 55 cal. AD (9.0%)	2060 – 1872 cal. BP (94.4%)

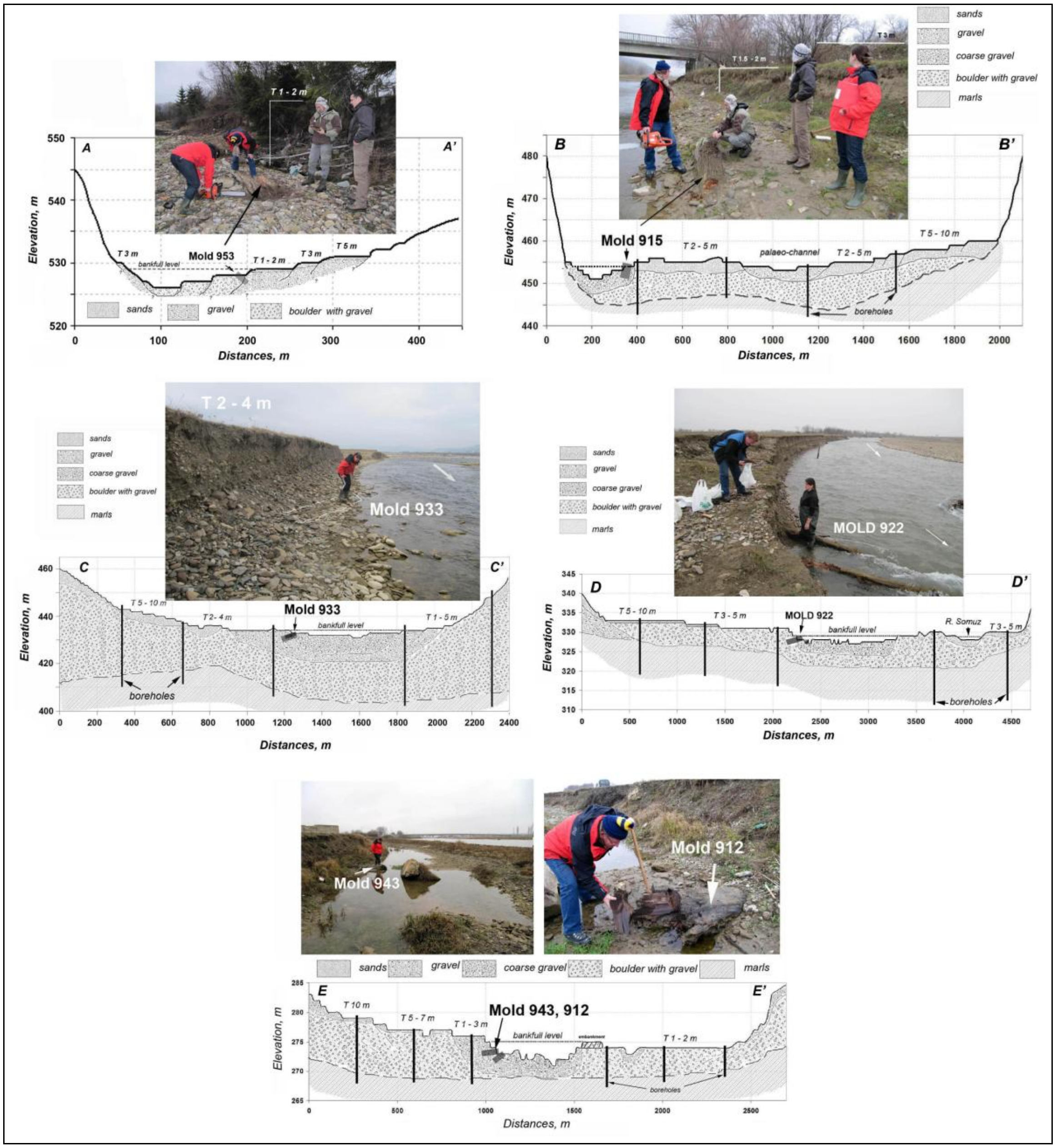

Fig. 14 Geomorphological profiles along Moldova valley: Molid (Mold 953); Gura Humorului (Mold 915); Slatina (Mold 933); Vadu Moldovei (Mold 922); Timişeşti (Mold 943,912) (Chiriloaei et al., 2012).

The main findings regarding the **milennial-scale dynamics of the fluvial processes along Moldova river** include the following aspects:

- four stages of increased fluvial activity were identified, during which the aggradation of the bed was prevalent, namely: 3100 years BP, 2000 years BP, 800-1000 years BP, 500 – 700 years BP (fig. 15).

- in relation to the climate variability, the stages of aggradation determined for Moldova river channel coincide with the colder, more humid periods which favoured the occurrence of exceptional floods throughout the study area. The Little Ice Age (cca.

1300-1850 A.D.), in particular, stands out in terms of the fluvial activity of the river during the late Holocene, as well.

- the warmer climate with lower precipitation, and, thus, diminished discharge values, established as from the 19th century, has resulted in fluvial activity dominated by incision and narrowing, especially after 1945 (in addition to the effects of the climate, the human interventions have nearly the same weight).

- the sedimentation rates of the channel of Moldova during the past 3000 years range from 1 to 6 mm/yr. Comparatively, the rates of incision of the river in its own alluvium during the past 30 years range from 0,3 mm/yr. to 4 mm/yr., indicating a highly accelerated activity of the present-day processes, which represents a threat to the mineral resources of the valley and the host to one of the richest groundwater resources in Romania.

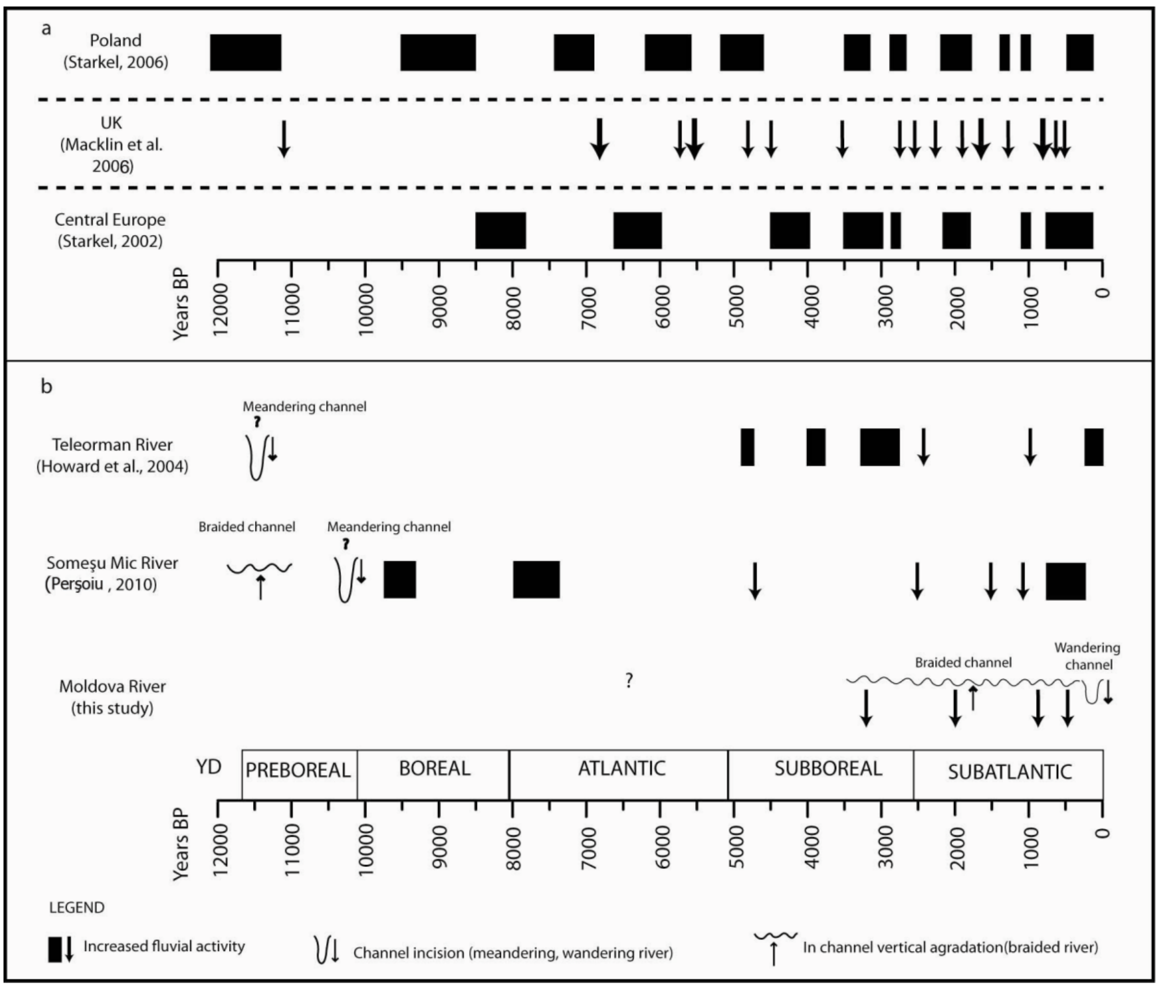

Fig. 15 Correlation between the fluvial activity in the Moldova river valley and other fluvial records from Romania (Chiriloaei et al., 2012). The data sources are Perşoiu (2010), Howard et al. (2004). The variation of atmospheric ^{14}C is taken from Stuiver şi Braziunas, 1993, cit. van der Leeuw et al., 2005

1.8. Model of evolution of the channel

The evolution model of Moldova river channel which comes into shape based on the data collected and processed by us covers the following types of adjustment of the channel: the first style is related to the vertical incision of the bed; the second type is connected to the planform narrowing of the channel by restraining its width; and the third style linked to the morphological changes in the channel, either from braided to *wandering* or the sinuous style with alternating bars, or from *wandering* to meandering or even sinuous. Each of these styles has prevailed differently along the study area, as suggestively shown in fig. 16.

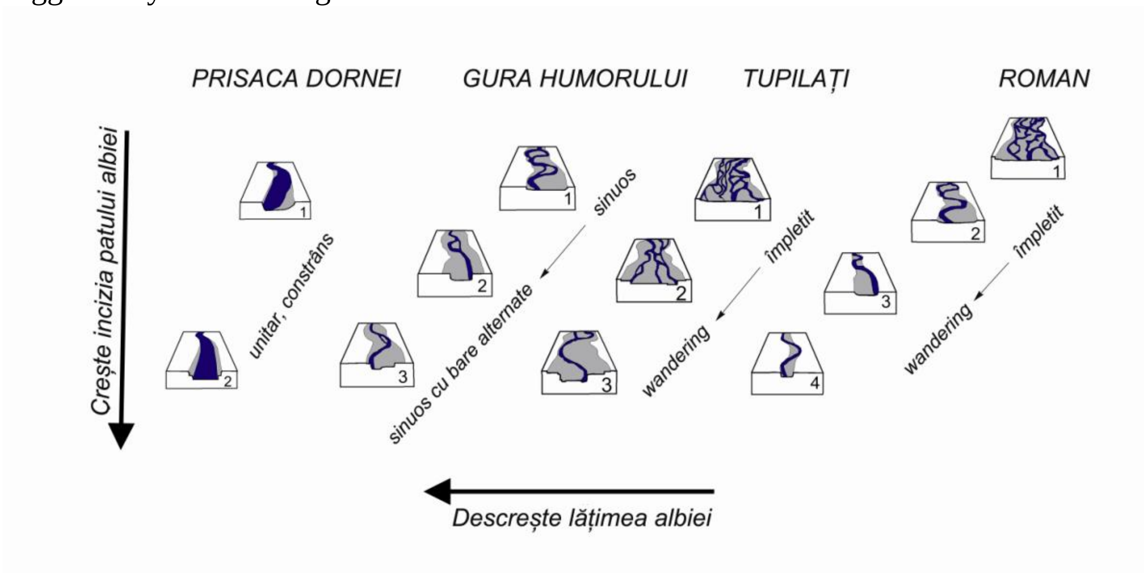

Fig. 16 Evolution diagram showing the main channel planform changes of Moldova river, as a result of incision and the initial morphological evolution

Fig. 17 Incision on Moldova river (Capu Codrului) b. Incision on Brenta river (Fontaniva)

Our observations are synchronous with those related by Surian et al. (2009a) (fig. 17b), as the 1980-1990 decade was marked by the greatest changes in river beds in Italy, France and Poland, as well as in Romania. It appears that a delay in the river channel response was documented in Romania, as compared to the rivers located throughout Western Europe. We believe this phenomenon is related to the amplest anthropogenic impact occurring in Eastern Europe much later than in had the West (Rădoane et al, 2012, in press).

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