Changes in the channel-bed level of the eastern Carpathian rivers: Climatic vs. human control over the last 50 years

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A B S T R A C T

This paper is focused on the changes over the past 50 years in the channel beds of seven major rivers that are part of the Siret drainage basin located in eastern Romania. Each river has been subjected to various degrees of human intervention, assessed based on the morphological quality index (MQI); two rivers (Siret and Bistriţa) have undergone complex human interventions on 40 and 60%, respectively, of their channel lengths, two rivers (Sucăvă and Moldova) are 30% artificial, and the remaining three rivers (Trotus, Putna, and Buzău) have a good or moderate MQI. The changes occurring in channel beds and data on water discharge ($Q_w$) and sediment load ($Q_s$) were assessed simultaneously for the last 50 years. The bedload was indirectly evaluated as ranging between 5 and 15% of the total sediment load. It was determined that incision was prevalent among the processes acting on the channel-bed sections under investigation (representing 62% of the altered area and changing bed level by between −0.25 and −2.70 m), with aggradation accounting for the remaining 38% (causing changes ranging from +0.15 to +1.25 m). The magnitude of the processes (incision or aggradation) for sections with an MQI < 0.3 was four times higher than for sections with a moderate or good MQI (>0.3).

The pattern of change in the channel-bed processes between 1960 and 2010 for all river categories was as follows: a low rate of incision from 1960 to 1979, followed by a higher rate of incision from 1980 to 1989, and finally a tendency of recovery toward the river’s initial state, characterised by a decrease in the incision rate or slight aggradation after 1990. The variable that exhibited the strongest response to climate conditions was water discharge ($Q_w$), whereas the sediment load ($Q_s$) was highly responsive to both climatic signals and anthropogenic factors. The sediment load has been instrumental in the adjustments of the channel beds by maintaining a balance between the two controlling factors, nature and man.

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1. Introduction

River channels are natural environments with great potential for change over time, particularly when the main control factors exhibit high short-term variability. The twentieth and twenty-first centuries have seen some of the most complex global climate changes in history; and the subsequent adjustments and changes, in landforms in general and in rivers in particular, have been widely documented (Hooke, 2000; Brierley and Fryirs, 2005; Goudie, 2005). Naturally, the results yielded by the extensive research in this field (e.g., Lièbault and Piégay, 2002; Rinaldi, 2003; Surian and Rinaldi, 2003; Gregory, 2006; Wyzga, 2008; Petcu and Rădoane, 2011; Buffington, 2012; Kiss and Blanka, 2012) have led to numerous arguments as to the degree of sensitivity of landforms to the action of natural control factors as opposed to anthropogenic factors. A general tendency of incision followed by channel narrowing and lateral stability has been reported for many European rivers over the past ca. 100 years (Table 7 summarises these changes). Two opposing views have emerged regarding the cause of this tendency: anthropogenic influences and natural causes (i.e., climatic changes associated with the end of the Little Ice Age and present-day warming) (Macklin and Lewin, 1997).

In support of anthropic causes of these changes, a series of authors (Gurnell, 1997; Surian, 1999; Winterbottom, 2000; Lièbault and Piégay, 2001, 2002; Marston et al., 2003; Rinaldi, 2003; Surian and Rinaldi, 2003; Surian and Cicotto, 2007; Wyzga, 2008; Zawiejska and Wyzga, 2010) have shown that alterations in the types and distribution of riparian vegetation, land use changes, gravel mining, and local and large-scale hydrotechnical works have altered flow discharge, sediment transport, and local stream power, thus leading to changes in channel behaviour and morphology.

Opposing this view, other authors (e.g., Rumsby and Macklin, 1996a,b; Psůt, 2002; Starkel, 2002; Uribelarra et al., 2003; Amstler et al., 2005; Rădoane et al., 2010; Persuoiu and Rădoane, 2011) have shown that climate changes and related changes in the frequency and amplitude of floods are an essential part of the historic dynamics of river channel, and that human interventions only modulate these
dynamics, most often by exacerbating the modifications induced by climate changes.

Romania’s river network has a total length of 76,000 km, draining an area of 237,500 km$^2$. Most of this network, 97.8%, comprises tributaries of the Danube River, which has an annual mean discharge of 1300 m$^3$/s, over 80% of which comes from the Carpathian Mountains. The results that have been reported for this region concerning river channel changes (Diaconu et al., 1962; Panin, 1976; Bondar et al., 1980; Ichim et al., 1989; Ichim and Rădoane, 1990; Pascu, 1999; Amârțiuă, 2000; Bondar, 2001; Rădoane et al., 2003, 2008a, 2008b, 2008c; Rădoane and Rădoane, 2005; Dumitriu, 2007; Feier and Rădoane, 2007; Cânciu, 2008; Persoșu, 2010; Armas et al., 2012) are mostly limited to certain river sectors, and they typically only address a particular dimension of the response of river channels to various factors (e.g., the adjustment of river channels downstream from dams; the effects of meander cutting and river channel corrections; the effects of decreasing sediment loads, etc.). As yet, there has been no clear quantitative evaluation of the changes occurring in river channels over a broader territory and over a period of time long enough to substantiate a trend in the evolution of Romanian rivers. Consequently, the present paper aims to provide such an evaluation.

Specifically, our endeavour aims to analyse the evolution of channel-bed changes over the past 50 years based on data from seven relevant rivers pertaining to the Siret drainage basin in Eastern Romania. The objectives of this study are as follows: (i) reconstruct the channel-bed changes; (ii) reveal the correlations between channel-bed adjustments and various human-induced alterations and climate changes; and (iii) present a comparative approach to the evolution of river channels in Romania as opposed to those from other European regions.

2. Study area and research methods

The research focuses on seven major rivers draining the eastern flank of the Eastern Carpathians, all of which are tributaries of the Siret River (Table 1). The main selection criterion was the varying degree to which the rivers have undergone human impacts, ranging from negligible interventions to large-scale changes that led to significant alterations in discharge and the sediment load (up to 80%), which granted representativeness to the selected rivers in terms of the range of impact in this area. Moreover, data availability is also factored into the selection of samples.

The main river, the Siret, has its origin in the Paleogene flysch in the Ukrainian Carpathians at 1238 m elevation. The length of the Siret within Romanian territory is 548 km, and the area of its drainage basin in Romania is 42,274 km$^2$, with an additional 1636 km$^2$ in Ukraine. Along its upstream reach, the river has created a typical transversal mountain valley, whereas in the ensuing reach the valley broadens into a wide couloir at its confluence with the Danube. The majority of its tributaries (with the notable exception of Bărlad, which is thoroughly adapted to the plateau region and is not included in the present study) originate in the Carpathian flysch, whereas just two of them—Moldova and Bistrita—penetrate the flysch to the internal crystalline strip of the Eastern Carpathians (Fig. 1). Primarily, because of the tectonics of the region and the occurrence of the subsidence area near the mouth of the Siret River, it is not uncommon that the tributaries of the Siret that originate in the Carpathians have diagonal trajectories that are nearly parallel to the Carpathian range north of the Trotus valley. From that point on, they become perpendicular to the Carpathian range as an adaptation to the complex tectonics of the Carpathian bend.

The distribution of lithologic units indicates a northward-oriented banded pattern, whereby the bands unfold eastward (Fig. 1). The volcanic zone only represents 1.33% of the Siret River basin and is composed of eruptive rocks. East of this region is a crystalline-Mesozoic area (6.79% of the basin’s area) represented by metamorphic rocks. East of the crystalline-Mesozoic area lies a flysch area (33.29% of the basin area), represented by a wide variety of sedimentary rocks. The next area to the east is characterised as Neogene molasses, made up of marls, clay, sandstones, and limestones interpolated with volcanic tuffs (10.12%); these materials are pleated but to a lesser degree than the flysch area. The largest part of the basin (47.94%) belongs to the Moldavian Platform, made up of marls, sands, sandstones, gravel, and oolitic limestone. The layers are slightly inclined SE, and where they contact the Neogene molasses, they are wavy.

The landforms situated on this particular substrate unfold eastward in the form of progressively lower steps and are fragmented by an asymmetrical stream network. The buildup of a well-individualised piedmont along the eastern frame of the Carpathians and Subcarpathians is an indicator of the consistently coarse sediment load carried by the stream network from the mountains. The area in question, well known to Romanian geomorphologists under the name of the Moldavian Piedmont, began its development as early as the Sarmatian and is partially eroded at present, particularly in the northern sector. Piedmont buildup processes are still active and are easily discernible in the behaviour of channel beds where they exit from the mountainous area (i.e., braiding or even avulsion; long profile deformation on the Siret River; Ichim and Rădoane, 1990).

One hundred and forty gauging stations are operational throughout the Siret drainage basin and measure stream discharge, of which 92 are further equipped to measure and record suspended sediment loads. Of these, 43 gauging stations located on the main rivers were selected for this study, each identified by an ordinal number (Table 1; Fig. 1) to which we will consistently refer throughout the paper. The aforementioned rivers were subject to detailed studies regarding the shape of their long profiles (Rădoane et al., 2003) and downstream variations in bed sediment (Rădoane et al., 2008b).

The data for each of the 43 cross sections comprised measurements of stream discharge (mean annual values), measurements of suspended sediment loads (mean annual values), and minimum annual water stages in the warm season (April to September) and cold season (December to March). We determined that of the latter two periods, the lowest values were recorded during the cold season. The annual minimum water stages were compared starting from the same reference plane. A subsequent decrease or increase in the minimum water stage of a river can then be interpreted as an effect of either incision or aggradation in the river bed, as water discharge values remained largely unchanged during these periods (Diaconu et al., 1962; Klimek, 1983, 1987). This method has been successfully employed in many rivers (Wyzga, 1993; Korpak, 2007) because it allows for a relatively rapid collection of data over broad areas and long periods of time. A time series of data on minimum water stages was available from 1960 to 2012 for six rivers out of seven (with the exception of the Buzâu River, where a complete data series is only available for a span of 10 years), whereas for the annual discharge and suspended sediment load, we obtained complete data series from 1950 to 2010 for all seven rivers included in the study.

3. Dimensions of the human impact on the Siret River drainage basin

A number of human interventions have occurred within the Siret River’s drainage basin (i.e., channelisation, sediment mining, dam construction, and deforestation), primarily during the past century. These interventions have both direct (e.g., levees, groins, and dams) and indirect (e.g., deforestation or reforestation) effects on channel dynamics. The history of human interventions in the area began during the twentieth century with the construction of bank protection structures, especially following the catastrophic 1970–1975 flood events. Natural reforestation, which followed several centuries of intense deforestation, has been most intense from the 1950s onward.
Among the most aggressive human interventions, we cite the significant reduction in forested areas. Whereas in the early eighteenth century the land cover of the Romanian territory included no less than 40% forests, during the elapsed time this category has decreased to 27% (considerably lower compared to the European average, 34%) (Giurgiu, 2010). The largest deforestation rates were recorded after 1950, such that between 1990 and 1989 compared to 0.2 million ha between 1990 and 2005, 1.5 million ha). Moreover, we argue that the process slowed after 1950, as in the case of the Putna River basin, such that between 1950 and 1989 such that between 1950 and 1989 compared to 0.2 million ha between 1990 and 2005, respectively. However, the rate of afforestation began to increase after 1950, as in the case of the Putna River basin, such that between 1950 and 1963, soil erosion dropped from 1800 to 2900 t km⁻² y⁻¹ on bare land and degraded pastureland to just 17–24 t km⁻² y⁻¹ on forested land (Gaspar and Cristescu, 1987).

According to the CORINE Land Cover (www.eea.europa.eu) methodology applied to the study area, between 1990 and 2006, deforestation has strongly prevailed compared to afforestation in the drainage basins included in our study area, so that each basin lost between 0.9 and 4.3% of its total forested area (Fig. 2; Table 2). The sole exceptions were the Putna River basin, which gained an additional 3.6% of forest area during the past 16 years, and the Buzau basin, where the forested area remained almost unchanged over the same time period. Gravel mining peaked in Romania during the communist era, when large-scale construction sites were opened (1970–1989). Although gravel mining diminished considerably after 1989, it has increased again in association with the economic relaunch of the 2000s. The rivers in the Siret River drainage basin account for over 33% of the gravel resources available in Romanian riverbeds (Călinou et al., 1988); therefore, extraction of gravel within this catchment has been consistently intensive. This activity was initiated during the 1960s, primarily for the construction of hydropower facilities, and continued through the 1970s and 1980s to support the large-scale construction of housing units.

Based on assessments dated 1976–1997 (Table 3), the annual mean rate of gravel extraction was as high as 7 million m³ in the Siret River system; by computing the volume of extracted gravel per surface unit of the source area, the extraction rate (382 m³ km⁻² y⁻¹) exceeded...
the regeneration rate of the channel-bed sediments by 138%. The sediment yield in the Siret basin upstream of the last operational gravel pit (A ~ 24,000 km²) was estimated based on a bedload of between 5 and 15% of the total sediment yield (Diaconu and Serban, 1994). This resulted in $\text{Sy} = 275$–300 m³ km⁻² y⁻¹ within the same reach of the Siret River, which provides an estimate of the natural generation rate of the channel-bed sediments. By subtracting the volume of mined gravel from the volume generated by the fluvial system, we found that the former exceeded by 2.5 million m³ the amount supplied by the river between 1976 and 1986. In 1976, one of the peak years in terms of gravel mining on the Siret River, the extraction rate amounted to three times the rate of sediment regeneration (Olariu and Gheorghe, 1999). After 1990, the amount of gravel mined from the channel beds decreased; however, the amount of extracted sediment remains rather high (62% between 2009 and 2011).

For the other rivers associated with the Siret basin, the only available data refer to the 2009–2011 period (Table 3). The Suceava and Moldova Rivers stand out in terms of gravel mining rates, with extracted volumes amounting to 45 and 54%, respectively, of the total volume supplied by the basins. Note that these are underestimates of the actual amounts of gravel extracted. The other rivers have provided lower amounts of gravel for mining. Although this
evaluation only accounts for a 3-year period, it allows for a larger perspective on how the 395 gravel pits have impacted the channel-bed level changes.

In addition to the gravel pits, no less than 260 dams have been constructed on the main Romanian rivers, which control over 13 billion cubic metres of water (amounting to one-third of the total discharge of the stream network). In an average period of 15 years, the reservoirs on the rivers collect deposits of ~200 million m³ of sediment. A total of 46 dams are functional within the study area, and 16 of these have reservoirs that retain the entire load of coarse sediments and over 50% of the fine sediments. The Siret and Bistrita Rivers have undergone the highest degree of interventions related to dam construction. The extent to which sediments are retained and remobilised along the Siret is shown in Fig. 3 and Table 4. By taking gauging station no. 1 (Siret) as a reference, the impact of the first two dams constructed on the Siret can be promptly observed at the Hutani gauging station (no 3), where the amount of sediment transported through the section line decreases by nearly 60%. Records from the following two gauging stations located downstream (Lespezi–no 4 and Drăgesti–no 6) show a relative recovery of the sediment load due to the input from the river bed as well as the contributions of two major tributaries, the Suceava and Moldova Rivers. The following series of three reservoirs, located close together (Galbeni, Răcăciuni, and Beresti), generate a severe decrease of 83% in the fine sediment load. The supply of fine sediments is restored to some extent downstream; nevertheless, it regains only 50% of the volume of sediments transported before the construction of the dams. The bedload, supplied primarily by the river's Carpathian tributaries, is confined to the sections located in between the dams and contributes to the adjustments of the channel-bed level as well as increasing the profits for mining companies.

In Table 4, the changes in water discharge and the sediment load along the Siret River after the construction of a succession of dams are shown separately. We believe that the increase in the amount of water transported by the Siret River by 5 to 14% during the post-dam period is an effect of climate variability (high waters in 1991, 2002, 2005, 2006, 2008, and 2010).

Regarding the Bistrita River, the construction of the Izvoru Muntelui Dam has completely modified the natural regime of discharge and

<table>
<thead>
<tr>
<th>River</th>
<th>Drainage area upstream from dams (%)</th>
<th>Dates of dam closure</th>
<th>Dates of construction of levees and other bank protection structures</th>
<th>Reforestation in the drainage basin (period/%)</th>
<th>Dates of intense deforestation</th>
</tr>
</thead>
</table>

* NA – not available.
sediment load transport over a distance of 125 km (42% of the total length of the river). Within this sector, the channel has evolved as an underfitted stream because after 1960 it was modelled by an amount of water of just 5% of the initial discharge (see Fig. 13(B)).

To conclude, based on the data collected over a long period of time from our own research (Rădoane et al., 2003, 2008b,c; Rădoane and Rădoane, 2005), as well as from the assessments made for this investigation of the seven selected rivers, we were able (based on expert judgement) to determine the Morphological Quality Index (MQI) (cf Rinaldi et al., 2013) for each river. The indicators used in the index were computed for the reaches upstream and downstream from the gauging stations and provide adequate spatial coverage, such that we may assess the morphological quality of the selected rivers. The resulting scores are included in Table 1 and have helped in estimating the proportion of each river’s length characterised by a high degree of artifi ciality and, conversely, the extent to which it remains in nearly natural conditions. The percentage values listed in Table 5 provide the most accurate depiction of the degree of human intervention in the selected rivers.

Thus, two of the rivers selected for this study (the Siret and Bistrita) have undergone complex human interventions on 40 to 60% of their channel length (MQI ≤ 0.3), two rivers (the Suceava and Moldova) have approximately a 30% degree of artifi ciality, whereas the remaining three rivers (the Trotus, Putna and Buzău) were ranked good or moderate (MQI ≥ 0.5). This variation allows us to discern and compare the extent to which river channel beds respond to the two major types of control factors, namely, climate variability and the human interference that has occurred over the past 50 years.

4. Climate variability in the Siret drainage basin and the responses of the multiannual regimes of discharge and sediment load

For the analysis of climate variability within the study area, we selected a data set of observations on precipitation that we were able to collect a data set of observations on precipitation that we were able to cater (MQI of bankfull discharge (which has maximum geomorphological eff ects) to demarcate trend categories: positive (\( b > 0.5 \)), relatively stationary (\( 0.5 < b < -0.5 \)), and negative (\( b < -0.5 \)). Data were interpolated using the Residual Kriging method, widely employed in climatological analyses (Tveito et al., 2006). In the yearly stage, we performed a multiple regression between trend values and altitude, longitude, and latitude of the pluviometric stations. The formula obtained was used to generate a map of the values distribution. The residuals obtained for each station were then interpolated by means of ordinary kriging and used for regional corrections on the initial map (Fig. 4).

In the north-eastern part of the study area, the precipitation series exhibit the most marked trends (\( b \approx 3.539 \)) because of heavy rainfall in 2005, 2006, and 2008, which surpassed the heavy rainfall recorded between 1970 and 1975. Overall, north of the Trotus River, the trend in the precipitation series is positive, albeit with low sensitivity in terms of the slope coefficient of the regression line. In the southeastern
part of the study area, the trend throughout the 60 years of precipitation records has been negative. The situation illustrated in Fig. 4 is confirmed by other studies for the geographical area of Romania (Stefan et al., 2004; Ionita et al., 2012) and has been linked to large-scale atmospheric circulation patterns. In particular, it has been shown that the North Atlantic Oscillation is the dominant atmospheric phenomenon that...
controls a large part of the interannual to decadal variability in precipitation and river flows in Europe and the Middle East (Hurrell, 1995).

The general trends in precipitation are expected to be mirrored by the water discharge. We will address this aspect in the following section.

The available database comprises the water discharge ($Q_w$) and suspended sediment load ($Q_s$) data series in the form of mean annual values for the 1950–2010 period. The maximum discharge series were not available from all of the observation points; however, for the few gauging stations where both data sets ($Q_w$ and $Q_{max}$) were available, we were able to verify the direct relationship between mean water discharge and maximum discharge. Moreover, the trends documented for the maximum annual discharge values (where they were available) showed a higher sensitivity (i.e., higher slope coefficient of the regression line) compared to the mean annual discharge values. Of the 43 investigated reaches, we determined the trends of the $Q_w$ and $Q_s$ variables for the reaches with a low degree of artificiality. The results are illustrated in Fig. 5 for the Carpathian tributaries of the Siret River. The trends over the last 60 years are depicted as columns proportional to the slope coefficient of the regression line.

The clustering of trend coefficients in the study area indicates that the Siret drainage basin is divided into two distinct parts, i.e., the northern sector, exhibiting a general tendency of increases in the amount of water and sediments, and the southern sector, where overall decreases in water discharge and sediment load were documented. In general, the suspended sediment load coefficients were consistently higher than the water discharge coefficients. By relating these data with the previously determined trends in annual rainfall, we may conclude that the climatic signal is strong in the responses of water discharge and suspended sediment load in the seven rivers. In the northern half of the Siret basin where annual rainfall is increasing, we determined that the values of mean discharge and suspended sediment load are also increasing. However, in the southern half, where the data indicate a slight drop in annual rainfall, the responses of the discharge and sediment load values are stronger in terms of the decreased rates recorded during the same period.

The response in the sediment load ($Q_s$) was considerably more sensitive to the climatic signal compared to the response in the water discharge for all analysed river sections. This differential response is maintained in the case of both increases and decreases in annual rainfall. The increasingly extreme climate and the insufficient number of anti-erosion works that have been constructed on slopes and elementary valleys during the past two decades have led to this augmentation in the amount of sediment reaching the main rivers from the Siret catchment. The mean mean annual value of the sediment yield in the catchment is 275–300 t km$^{-2}$ y$^{-1}$, higher than the average of 206 t km$^{-2}$ y$^{-1}$ calculated for the Romanian territory.

Anthropogenic causes have been widely invoked in a large number of papers that have a more or less global scope as being instrumental in the decline of sediment loads; among these causes, dams are considered dominant in the hierarchy of control factors from their direct interference in sediment retention and the decrease in the sediment load of rivers downstream from dams (Walling, 2009). However, despite the amount of sediment retained in reservoirs, research conducted by Svitski et al. (2005) has shown that “human activity was estimated to have increased the global land-ocean suspended sediment flux by approximately 16% from a pre-human value of 14 Gt year$^{-1}$ to 16.2 Gt year$^{-1}$, although sediment trapped by dams reduced this by ca. 22% to 12.6 Gt year$^{-1}$ (cit. Walling, 2006, p. 212).

At the scale of the Siret basin, we can illustrate this effect on the sediment flux by comparing two contrasting situations in terms of the degree of human intervention and the size of the river basin: a small-sized basin with 33% forest cover (the Suceava River, upstream of section no. 11) and the Siret basin in Lungoci (no. 9), which subsumes the entire range of anthropogenic interventions, including 46 reservoirs, of which 6 are located on the Siret River itself. The result of the comparison is presented in Fig. 6. Thus, we determined that 1991 was a turning point for the Siret River regarding the dynamics of sediment load, after all six dams upstream became functional (albeit some of them had been operational since 1977). Conversely, the data on a river free of almost any anthropogenic interventions (the Suceava River in the Brodina section, no. 11) illustrate how the increase in discharge post-1991 (marked by successive high waters in 1995, 2002, 2008, and 2010) has resulted in the augmentation of the suspended sediment load carried by the river. The two types of antithetical charts (Fig. 6) clearly illustrate the manner in which the sediment load is sensitive to the two classes of control factors: climatic and anthropogenic.

The analysis performed by Walling and Fang (2003) on the Yellow River has ascertained that a progressive reduction in water discharge and sediment load occurred between 1950 and 2000, thus showing that the change is a response to climate signals (namely, a decrease in the annual precipitation within the river basin) and the various human interventions (particularly the construction of several dams in the drainage basin). According to the evaluation by Wang et al. (2007) for the Yellow River, the decrease in precipitation is responsible for 30% of the decrease in sediment load, whereas the remaining 70% of the change is ascribed to human activities in the river basin.

To conclude, the rivers of the Siret River basin, representing a range of intensities of anthropogenic interference, exhibit sensitivity in the responses of water discharge and sediment load to climatic signals (particularly the variations in annual rainfall), albeit with low statistical significance. The sole human intervention that is significant

<table>
<thead>
<tr>
<th>River cross section</th>
<th>Period</th>
<th>Change in water discharge (%)</th>
<th>Change in sediment load (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siret (1)</td>
<td>1950–1978</td>
<td>1979–2010</td>
<td>105.6</td>
</tr>
<tr>
<td>Hutani (3)</td>
<td>1950–1978</td>
<td>1979–2010</td>
<td>113.9</td>
</tr>
<tr>
<td>Lepești (4)</td>
<td>1950–1978</td>
<td>1979–2010</td>
<td>109.8</td>
</tr>
<tr>
<td>Dragesti (6)</td>
<td>1950–1978</td>
<td>1979–2010</td>
<td>114.2</td>
</tr>
<tr>
<td>Racatau/Adjudu Vechi (7)</td>
<td>1950–1983</td>
<td>1984–2010</td>
<td>114.0</td>
</tr>
<tr>
<td>Lungoci (9)</td>
<td>1950–1983</td>
<td>1984–2010</td>
<td>108.3</td>
</tr>
</tbody>
</table>

Table 4: Changes (as percentages) in water discharge and the sediment load along the Siret River during the pre-dam and post-dam periods.

<table>
<thead>
<tr>
<th>River</th>
<th>Poor (%)</th>
<th>Moderate (%)</th>
<th>Good (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siret</td>
<td>60</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>Suceava</td>
<td>30</td>
<td>47</td>
<td>23</td>
</tr>
<tr>
<td>Moldova</td>
<td>30</td>
<td>45</td>
<td>25</td>
</tr>
<tr>
<td>Bistrița</td>
<td>43</td>
<td>11</td>
<td>46</td>
</tr>
<tr>
<td>Buzau</td>
<td>15</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>Trottis</td>
<td>3</td>
<td>29</td>
<td>68</td>
</tr>
<tr>
<td>Putna</td>
<td>2</td>
<td>41</td>
<td>57</td>
</tr>
</tbody>
</table>

Table 5: Percentages of each river’s length characterised by the following classes of morphological quality (MQI): good, MQI ≥ 0.7; moderate, 0.3 ≤ MQI < 0.7; poor, MQI ≤ 0.3.
in terms of the change in the amount of sediment transported by a river is the construction of cascading dams on two of the seven rivers, whereas other types of interventions (e.g., land use and land cover changes, levees and groins, gravel mining, etc.) are overwhelmed by the strong influence of the climatic signal on the variability of $Q_w$ and $Q_s$.

In the next section of the paper, we investigate the changes in the channel-bed level and attempt to determine which anthropogenic interventions are relevant to the adjustments of the channel beds.

5. Changes in the channel beds in the Siret drainage basin over the last 50 years

The data series on channel-bed height spans over 50 years (1960–2010) for 90% of the selected river sections, whereas the other data series analysed previously ($Q_w$ and $Q_s$) spanned 60 years. The vast majority of the rivers in the study area have gravel beds—i.e., 1345 km of the rivers’ length ($D_{50}$ is given in Table 1) whereas the lower courses
of the Siret, Putna, and Buzau Rivers (i.e., 312 km) have sandy beds. Thus, this translates into bedload values ranging from 5 to 15% with a maximum of 35% (according to the theoretical assessments made within the river monitoring system; Diaconu and Serban, 1994). The data on the minimum annual level of the river (in cm, identified by the bed level variable, $BL$) were plotted according to the model in Fig. 7, which shows the channel-bed changes in the 10 sections where measurements were performed on the Siret River.

The available database was processed following the methodology presented above. The plots obtained for each river section provided preliminary information on the state of the channel bed during the time period subject to this analysis (i.e., whether the channel bed has aggraded, degraded, or remained relatively stable, the magnitude of any change and when it occurred).

Fig. 7 shows that incision appears to have been the prevailing process across all 10 sections along the Siret River during the 50-year period. Analogous charts were created for each river section under investigation to discern which factors contributed to each distinct state of evolution of the channel bed. The changes in the channel bed were related to the variations in the discharge and sediment load within each river section; thus, the model displayed in Fig. 8 was replicated for all of the sections (except for the $Q_{\text{max}}$ data, which were not available for all investigated rivers). Fig. 8 shows the maximum discharge ($Q_{\text{max}}$), mean discharge ($Q_{\text{w}}$), suspended sediment load ($Q_s$) and bed level ($BL$) data series recorded in sections Siret (no. 1) and Lungoci (no. 10). Section no. 1 is located upstream at the Ukrainian border, and thus, we have no information regarding any major anthropogenic interventions; however, section no. 10 exhibits the cumulative effects of dam construction (six structures built between 1977 and 2004), gravel mining, and various other interventions on tributaries. By comparatively assessing the responses of the channel bed within the two opposite sections of the Siret River, two points were noted: where there have been no major human interventions (such as dams) in the river’s processes (i.e., 98 km from the river’s headwaters), the channel bed has continually deepened since 1960 by as much as 1.77 m; 648 km from the river’s headwaters, downstream from multiple major anthropogenic interventions, the onset of incision began post-1985 when the first dam became operational on the Siret.

In section no. 1, $Q_{\text{max}}$ increased after 1979 by as much as 450%, whereas $Q_w$ rose by 105% and $Q_s$ by 118% (the bedload was estimated as <5%). Under these circumstances, we would expect the bed level to be at least stationary or undergoing slight aggradation. In fact, the incision occurring in this section is the highest among all 10 sections along the Siret River. We detailed the data series and determined that, although the overall trend of $Q_s$ is increasing, there were periods (1986–2005) when the suspended sediment load declined dramatically (by 47%). During the same period, the rate of bed incision increased. However, after 2005, the sediment load carried by the river increased such that the bed level has exhibited a slight recovery.

Within the other river sections up to section no. 10, the amount of incision diminishes to such an extent that (during certain time frames) aggradation becomes dominant. We documented the reason for this pattern in several earlier papers (Ichim and Radoane, 1990; Radoane et al., 2008c): the source of fine and coarse sediment supplied by the Carpathian area through the main tributaries of the Siret River (the Suceava, Moldova, Trotus, and Putna) contributes to a decrease in the rate of incision along the river.

In the next section of the paper, we will look into the changes in the channel-bed level and attempt to determine which anthropogenic interventions are relevant to bed level adjustments.
Fig. 6. Recent trends in suspended sediment yield for two rivers (under human control and climatic control) using the associated double mass plot.

Fig. 7. Temporal trends in bed-level changes along the Siret River. 1 → 10 are gauging stations numbered according to Table 1 and Fig. 1.
5.1. Spatial trends in channel-bed level adjustments

The spatial trends in the evolution of the channel beds of the Carpathian rivers that are part of the study area are summarised in Fig. 9. Each column shows the maximum absolute value of the bed level (in cm) between 1960 and 2010 at the gauging stations along the river (whose positions are designated by the distance from the river headwaters to the respective gauge station, in km). Thus, we can create an accurate image of the behaviour of the rivers in the study area. The rivers were classified according to the degree of human interventions assigned in Table 5, and the analysis of each case ensued.

5.1.1. River group A (moderate and good MQIs)

The Trotus, Putna, and Bistrita Rivers (the latter upstream of the Izvoru Muntelui Reservoir, \( L = 167 \) km) have undergone the least amount of direct human interventions (whereas indirect interferences have primarily included the change in forest cover within the drainage basins—Fig. 2, Table 2), which prompted their inclusion in class A.

5.1.1.1. Trotus River (Fig. 9(A)). In the mountain sector (section no. 27), the bed level had relatively low vertical variations (~40 or 50 cm) and an overall rising trend. Downstream, the river diagonally crosses an area that holds great potential for sediment delivery, generated by the small catchments discharging coarse sediments directly into the main river channel (Dumitriu, 2007). Consequently, the response of the channel bed has displayed a varying trend over the past 30–50 years (aggradation in section no. 29, incision in sections 28, 30, and 31). In the extra-Carpathian reach, in the closing area of the basin, aggradation was prevalent between 1960 and 2000 (see the image of the railway.
bridge nearly buried in sediments shown in Fig. 15(A)); however, following that period, the onset of incision was documented. Overall, if we average all of the channel-bed level values, the resulting trend indicates a prevailing degradation process on the Trotus River, although the incision value for the last 50 years has been almost negligible (−23 cm).

5.1.1.2. Putna River (Fig. 9(A)). This river is dominated by aggradation throughout all four Carpathian (no. 33) and Subcarpathian (34, 35, 36) reaches. The most prolific Romanian region in terms of sediment yield (along with the Buzau basin) (Ichim et al., 1998) has been on an upward trend during the past 50 years. The increase in forested area in the Putna basin by over 7% during the last century has not been able to significantly reduce the amount of sediment transferred from the hillslopes to the channel bed. The majority of this stock of sediment is then deposited in the outer Carpathian Piedmont area, such that toward the confluence with the Siret River the Putna acquires sufficient energy to have generated a 1-m-deep incision between 1960 and 2010.

5.1.1.3. Bistrita River (Fig. 9(C), the mountain sector). We included in this category the 167-km-long mountainous sector that has undergone minor human interventions and is characterised by a narrow valley with an entrenched channel and coarse alluvial bed. Incision is the prevailing process throughout this sector, albeit the magnitude of the incision is relatively low, ca. 50 cm over the period of 50 years under investigation. Upstream from the Izvoru Muntelui Dam (section no. 24), a slight aggradation of the bed has been documented (+0.20 cm) during the aforementioned time interval, likely the effect of the rising base level (also see Fig. 15(D)).

To conclude, the rivers included in group A are singular within the study area because they have undergone processes of aggradation and degradation of the channel-bed level during the same period of time along the same river. In the absence of any direct or major human interventions, the analysed rivers have adjusted by means of aggradation/degradation to a slightly positive trend in the water discharge and sediment load along the river.

5.1.2. River group B (with poor, moderate and good MQIs)

The Suceava and Moldova Rivers were included in this class because of the moderate direct interventions that their channel beds have been subjected to, mainly gravel mining and the change in forest cover (Fig. 2, Table 2). This group also includes the Buzau River; however, the short data series available, comprising bed level measurements over a period of just 10 years, does not allow for a comprehensive discussion of this river.

5.1.2.1. Suceava River (Fig. 9(B)). The channel bed was monitored in three sections along the Suceava River whose parameters are described below. Section Brodina (no. 11), located in the mountainous area where the bed is composed of gravel and boulders, underwent a process of abrupt incision of 50 cm during the major flood event in 1970; during the following decades, the bed has struggled to recover the pre-1970 bed level. At the downstream end of the mountainous sector (section no 13), the general tendency of the bed was to deepen by over 1 m during the first 30 years. Construction

![Fig. 9. Generalised trends in bed-level changes along the studied rivers.](image-url)
projects transversal to the channel, such as bridges or power lines, were the first to be affected by the incision of the channel-bed level (see Fig. 15(B)). Although during the following 10–15 years the channel bed tended to recover slightly, it has not been restored to the previous bed level.

5.1.2.2. Moldova River (Fig. 9(B)). The main process documented in five of the six sections wherein the channel-bed level was monitored during the investigated period was incision. Along the river, the overall incision of the bed was lower in the mountainous area and higher in the extra-Carpathan sector. No abrupt changes were documented in the bed level; instead, we found that the channel bed has undergone a process of continuous incision that has lowered the bed level nearly 3 m over the past 50 years.

To conclude, the rivers included in group B are defined by generalised incision of the bed, as the discharge and sediment load carried by the rivers have slightly increased during the same period. Gravel mining (Fig. 15(C)) and the lowering of the base level of the Siret River have both contributed to enhancing the state of degradation along the rivers (Fig. 15(F)), whereby the highest values are reached at the junction with the Siret River (sections 13 and 19).

5.1.3. River group C (with poor and moderate MQIs)

This class includes the Bistrita (the last 125 km) and Siret Rivers, which are defined by large changes in the water discharge and sediment load due to dams and channelling in the former case and dams in the latter.

5.1.3.1. Bistrita River (Fig. 9(C)). Downstream from the Izvoru Muntelui Reservoir, the river (L = 125 km) is completely transformed by the construction of a channel that receives the entire water discharge of the upstream river. The natural channel of the river receives just 9% of the initial discharge. Consequently, aggradation is prevalent as a result of the state of underfitness of the channel to the new water discharge conditions. Therefore, in section no. 26 (Frunzeni), the channel-bed level has risen by 96 cm between 1960 and 2010.

5.1.3.2. Siret River (Fig. 9(C)). Throughout the entire 550-km length of the Siret River, the dominant process was generalised incision in all 10 sections where the channel-bed level was investigated. At the beginning of this chapter, we discussed the case of this river (Fig. 7). We documented a downward trend in the deepening of the channel bed along the river. The highest incisions occurred upstream of the confluence with the Suceava River (where the river receives no major Carpathian tributaries). Further downstream, the deepening of the channel becomes less pronounced as the Siret River incorporates six Carpathian tributaries. Further downstream, the incision becomes lower. Over the investigated period (the 1990s and the 2000s), we observed the decadal behaviour of the channel beds between 1980 and 2010 using the same simple technique of trend coefficients.

The first case (Fig. 11) addresses the 23 sections with morphological quality index values above 0.3. The decadal behaviour of the channel beds with low artificiality exhibits a large variability in the trend coefficients. However, in the variation of all of the statistical indicators, an average state is easily identifiable that distinguishes between the first part of the interval (with a tendency toward incision of the bed) and the second part (with a slight aggradation tendency). The largest scattering around the average was recorded in the 1970–1979 decade, when some of the greatest floods occurred in Romania; the response of the channel bed consisted of either excessive aggradation (Suceava, section no. 11; Putna, section no. 34) or abrupt incision (Moldova, section no. 17; Trotus, section no. 28). Toward the end of the investigated period (the 1990s and the 2000s) the statistical indicators show a lower dispersion around the average, hence the observation that channel-bed level recovery by aggradation has occurred in most cases (Fig. 11).

For comparison, we attach the same type of statistical processing applied for the two control factors directly involved in the morphological changes in the channel-bed level, the water discharge ($Q_w$) and the sediment load ($Q_s$) (Fig. 12). Only 17 reaches were selected because not all of the sections monitored for $BL$ are also equipped for sediment load measurements.

The first emerging observation concerns the degree of concentration of the values around the mean, allowing us to deduce that the data series are much more evenly distributed for the 17 reaches we considered. The degree of uniformity was better for $Q_w$ than for $Q_s$ as was expected.

The second observation concerns the amplitude of the decadal variation in $Q_w$ and $Q_s$, which is more nuanced in the case of $Q_s$ and less so for $Q_w$. The climate variability leaves a stronger mark on $Q_s$ compared to $Q_w$, which makes sense given the increasing complexity of the disturbance factors within the cascade of the processes in question.

The third observation relates to the synchronisation of the decadal oscillations of the two variables: increases during the decades...
1960–69 and 1990–99 (the same trend is maintained in the case of the sediment load during the 2000–2010 decade) and declines through the 1980 to 1989 decade.

Without making too bold a statement, we can easily observe a common trait in the decadal variations of the three variables under discussion, $Q_w$, $Q_s$ and $BL$, albeit it is more apparent for the former two ($Q_w$ and $Q_s$) and less sharp in the case of $BL$. The diminishing role of the climatic factor within the cascade of drainage processes ($Q_w$), followed by its decreasing role in sediment release and transport ($Q_s$) and in the behaviour of the channel-bed level ($BL$), occurs as other factors (such as the geology and relief of the river basin, land use, direct anthropogenic interference, etc.) intervene and disrupt the variability initially induced. However, even considering the very low sensitivity of the $BL$ response to the climatic factor, we cannot avoid acknowledging that river channels become efficient not so much when the water discharge is high but in instances where there is a low suspended sediment load. A moderate discharge complemented by a low sediment load is more geomorphologically effective than a catastrophic flood. This conclusion confirms yet again that “geomorphological work” is accomplished if a process or a combination of processes show sufficient ability (i.e., finding the optimal interference between the frequency and magnitude of processes) (Wolman and Gerson, 1978).

In the second case (Fig. 13(A)), we introduce the situation of the 15 channel cross sections for which the morphological quality index was below 0.3. Throughout the entire investigated time frame, we documented that channel-bed level incision was characteristic of all of the sections with MQIs below 0.3, with the exceptions of two sections (no. 25 and no. 26 on the Bistrita River) where aggradation was the dominant process (Fig. 13(B)).

The decadal analysis of channel behaviour indicated that incision and aggradation were not linear processes in this case, either. The
Fig. 12. Decadal trends for water discharge ($Q_w$) and sediment load ($Q_s$) for the river-channel cross sections with MQI > 0.3.

Fig. 13. (A) Decadal trends of bed-level for 15 river-channel cross sections with a high degree of artificiality (MQI < 0.3); (B) Bistrita River channel 6 km downstream from the Izvoru Muntelui dam, controlled by a flow representing 9% of the initial flow. The tributaries release sediment into the channel bed, leading to aggradation. (photo N. Rădoane).
1980–1990 decade appears to be the most dynamic in terms of the rate of channel-bed level change, as well. During this period, most of the dams on the Siret River became functional, which resulted in reducing by half the amount of transported sediment and regularising the water discharge, whereas the activity of gravel pits led to exceeding by 138% the regeneration rate of the coarse sediment within the channel beds.

During the same period, we found that the climatic factor manifested as a decrease in water discharge, which also played a part in reducing the sediment transfer within the fluvial system (Fig. 14). The latter was perceived to an even greater extent than in the previous decade (1970–1980) owing to multiple human interventions.

As with the sections where MQI > 0.3, for the channel beds with a high degree of artificiality, the 1990–2000 decade was defined by a tendency of recovery toward the previous state of the channel-bed level; the elevation of the channel-bed level by aggradation is visible in the diagram from Fig. 13 in the flexure of the mean curve as well as the reduced dispersion around the average. Set against a climatic background favourable to increasing water discharge (by 5–14%, according to Table 4) and sediment loads, human interventions no longer had the magnitude of those that occurred in previous decades. Gravel mining (directly altering the channel-bed level) decreased to 64% of the total sediment yield of the Siret basin whereas just one dam became functional in June 2004, such that the fluvial system had sufficient resources to attempt to balance its dynamic state (Fig. 13(A)), although it could not match its state prior to 1970.

To conclude, the mirror analysis of the decadal behaviour of river-channel beds in the Siret basin yielded the following:

- The majority of the sections found in quasinatural conditions were dominated by incision of the channel bed during the 1970–1979 and 1980–1989 decades, then in subsequent decades (1990–1999 and 2000–2009) the incision was reduced and slight aggradation was initiated in some instances.
- Within the river sections controlled by anthropogenic interventions, Qw is the variable that has the strongest influence in terms of bed level changes, as well. The time period in which five reservoirs all became operational on the Siret River, thus actively retaining a large amount of sediment, occurred during a decade when the river discharge was on a climate-induced downturn. In some instances, the rate of decrease in Qs was as high as 10 times the rate of reduction in Qw, therefore resulting in the incision of the bed. Moreover, it was the signal conveyed by the Qs variability that generated the tendency toward recovery in some river sections, ranging from decreased incision to slight aggradation.

6. Discussions and conclusions

The results obtained so far for the Siret drainage basin greatly enhance the understanding of the circumstances under which changes in water discharge and sediment loads, whether quasinatural or human-induced, contribute to the onset of a certain type of response in the channel bed. The argument presented by Schumm (1977) in his conceptual approach to river metamorphosis was confirmed by our observations. Therefore, we have added our own conclusions, inferred from the results of the present study, to Schumm’s conceptual scheme (1977) (Table 6). Our contribution regards the nuances of the relationships between Qw and Qs and the response of the channel bed in terms of either incision or recovery (i.e., recovery of the bed level prior to the onset of incision), separated according to the level of disturbance: quasinatural vs. anthropogenic.

In this stage of the research, we have no data regarding changes in the width of the river channels under investigation to correlate with the changes in the bed level. Several studies on this matter, which are listed in Table 7 reported that channel narrowing during the past century has been a regular process in river-channel morphodynamics in Romania. The most representative case is the Moldova River, for which Chiriloiade et al. (2012) determined a narrowing by ~80% of the channel width between 1910 and 2005 for a 110-km-long reach. Within the same reach, in this study, we identified a deepening of the channel bed by as much as 3 m.

By correlating the response of the bed level, BL, with the size of Qw and Qs, we observed that over the medium term the regulator of the two variables is the change in the sediment load (Qs). For example, a decrease by one unit of Qw (Qw − 1) resulted in a reduction of Qs by 2 (Qs − 2×) to 3 times as high (Qs + 3×) (and that occurred in the 1980–1990 decade, when the onset of channel-bed incision was the prevailing process, BL = 1). Conversely, an increase in Qw by 1 unit (Qw + 1) led to an increase in Qs 1 (Qs + 1×) to 4 (Qs + 4×) times as high, which promptly resulted in a tendency of recovery of the channel-bed level by aggradation (during decades 1990–1999 and 2000–2010).

The movement of suspended sediments and the bedload within fluvial systems is not a simple enough process to be controlled solely by the climatic factor. The positive and negative changes in the sediment load show the high degree of sensitivity of this variable to both climate changes (through the signal transmitted via Qw) and anthropogenic interventions. The sensitivity of Qs has been documented in all of the rivers under investigation, regardless of their degree of artificiality; however, it is more apparent in the rivers where human control is prevalent. The sole river showing no response to the climatic signal (because of the quasi-absolute human control over Qw) is the Bistrita

![Fig. 14. Decadal trends for water discharge (Qw) and sediment discharge (Qs) of the river-channel cross sections with MQI < 0.3.](image-url)
River downstream of the Izvoru Muntelui Reservoir, where the channel bed has undergone significant aggradation (by nearly 1 m), whereas all 9 anthropogenically controlled sections along the Siret River were undergoing incision during the same decade (1980–1989: Fig. 13(A)).

Based on the evidence provided, we have reason to conclude that in the sections with anthropogenic control, the climate signal is still evident despite the anthropogenic impact.

The results obtained thus far by studying the rivers of the Siret basin are certainly not singular in the literature, but they are the outcome of the first approach in terms of level of analysis for this geographic area of Romania. Table 7 summarises several studies from various regions in Europe spanning the last century. The data suggest extensive interest in assessing the magnitude and causality of changes and thus substantiating a better management of rivers. The aspects that we would like to particularly highlight include the magnitude of channel adjustments, the temporal trends of channel changes, and the causes cited for these changes.

In terms of the magnitude of channel adjustments, we determined that rivers in Italy have undergone the most substantial changes in size parameters (incision up to 10 m in depth and channel narrowing up to 80%) (Surian and Rinaldi, 2003; Surian et al., 2009a,b). Similar or somewhat lower incision rates and channel narrowing have been documented in rivers from other regions, such as the French Alps, southeastern France, Scotland, and the Polish Carpathians (Table 7). Moreover, river metamorphosis in recent times was not confined to the European territory and was also documented in China, South

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**Fig. 15.** Examples of the current state of several river channels pertaining to Siret drainage basin: (A) River Trotus 10 km upstream of the confluence with R. Siret, where the railway bridge pillars were buried caused by aggradation of the bed (photo N. Rădoane); (B) River Suceava 50 km upstream of the confluence with R. Siret, where the bridge was destabilised owing to the degradation of the channel bed (photo N. Rădoane); (C) Gravel mining on Suceava River channel (photo V. Efros); (D) Channel bed aggradation on Bistrita River upstream of Izvoru Muntelui Reservoir (photo N. Rădoane); (E) Incision of the bed on Milcov River, tributary of River Putna (photo R. Săcrieru); (F) River Moldova 95 km upstream of the confluence with R. Siret, incision of 1.5 m (photo N. Rădoane).
In the Siret drainage basin exhibit a rather low amount of incision. Throughout the European continent over the past century, the rivers and channel narrowing have been the norm in river geomorphology (with magnitudes ranging from 0.15 to 1.25 m). Although incision remaining channel sections aggradation was the dominant process have been less extensive in Romania in terms of incision depths during the twentieth century, we should noted that adjustments 2006; Simon and Rinaldi, 2006; Li et al., 2007).

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Table 6
Geomorphic impacts on channels of changes in water and sediment leading to river bed morphology.

<table>
<thead>
<tr>
<th>Change</th>
<th>River bed morphology</th>
<th>Change</th>
<th>River bed morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1 + Qw =</td>
<td>Aggradation, channel instability, wider and shallower channel</td>
<td>Q1 + Qw =</td>
<td>Aggradation</td>
</tr>
<tr>
<td>Q1 − Qw =</td>
<td>Incision, channel instability, narrower and deeper channel</td>
<td>Q1 + Qw =</td>
<td>Processes increased in intensity</td>
</tr>
<tr>
<td>Q1 + Qw =</td>
<td>Aggradation, channel instability, narrower and shallower channel</td>
<td>Q1 − Qw =</td>
<td>Processes decreased in intensity</td>
</tr>
<tr>
<td>Q1 − Qw =</td>
<td>Incision, channel instability, deeper, wider? channel</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Qw + 1: increase in water discharge by 1 unit; Qw + 1.5: increase in the sediment load by 1.5 times as much as the water discharge; Qw − 1: decrease in water discharge by 1 unit; Qw − 3: decrease in the sediment load by 3 times as much as Qw; BL = -: stability or incision of the bed level; BL = +: stability or aggradation of the bed level.

In our opinion, the reason for this is that the sediment transport rate from the source area to the delivery area is considerably higher in our study area than in other European regions. The values depicting the sediment output within the Siret basin are telling: 277 t km⁻² y⁻¹, compared to 206 t km⁻² y⁻¹ for the rest of the Romanian territory and 166 t km⁻² y⁻¹ for the Bulgarian territory (Gergov, 1996). According to the spatial pattern established by Vanmaecke et al. (2011) for Europe, the sediment output measured in the Siret basin falls into the European mountain and Mediterranean type, which ranks highest in the classification (over 200–600 t km⁻² year⁻¹). The highest values, amounting to 30,000 t km⁻² year⁻¹, were recorded in basins from Spain, Italy, and Turkey). Within the Romanian territory,

Table 7
Data on the recent channel changes in some European rivers over the last 100 years: (−) incision; (+) aggradation.

<table>
<thead>
<tr>
<th>River</th>
<th>Country</th>
<th>A (km²)</th>
<th>Q (m³/s)</th>
<th>Studied river length (km)</th>
<th>Incision, m 20th Century</th>
<th>Last 30–40 years</th>
<th>Narrowing, %</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miszańka</td>
<td>Poland</td>
<td>175</td>
<td>52</td>
<td>19.5</td>
<td>−1.2...−2.0</td>
<td>40</td>
<td>Wyzga (1993)</td>
<td></td>
</tr>
<tr>
<td>Porepihania</td>
<td>Poland</td>
<td>12.1</td>
<td>5.5</td>
<td>250</td>
<td>−3.1</td>
<td>45</td>
<td>Wyzga (2008)</td>
<td></td>
</tr>
<tr>
<td>Raba</td>
<td>Poland</td>
<td>6804</td>
<td>15.9</td>
<td>7.1</td>
<td>−3.1</td>
<td>45</td>
<td>Wyzga (2008)</td>
<td></td>
</tr>
<tr>
<td>Polish Carpathian rivers</td>
<td>Poland</td>
<td>1.5</td>
<td>7.1</td>
<td>1.5...−7</td>
<td>−2.4</td>
<td>Narrowing</td>
<td>Marston et al. (2003)</td>
<td></td>
</tr>
<tr>
<td>Malnart</td>
<td>France</td>
<td>600</td>
<td>1.5</td>
<td>8</td>
<td>−1.06</td>
<td>67</td>
<td>Liebault and Piegay (2001)</td>
<td></td>
</tr>
<tr>
<td>Roubon</td>
<td>France</td>
<td>1150</td>
<td>1.8</td>
<td>102</td>
<td>−1.51...−3.04</td>
<td>54-77</td>
<td>Liebault and Piegay (2002)</td>
<td></td>
</tr>
<tr>
<td>Egyges</td>
<td>Mountain and Piedmont rivers, SE France</td>
<td>63...17600</td>
<td>1.06</td>
<td>67</td>
<td>−1.31 ± 0.6</td>
<td>55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arno</td>
<td>Italy</td>
<td>8830</td>
<td>97.4</td>
<td>198</td>
<td>Up to −9</td>
<td>38–50</td>
<td>Rinaldi and Simon (1998)</td>
<td></td>
</tr>
<tr>
<td>Tagliamento</td>
<td>Italy</td>
<td>2580</td>
<td>109.0</td>
<td>178</td>
<td>−1.5...−3.0</td>
<td>58</td>
<td>Surian and Rinaldi (2003)</td>
<td></td>
</tr>
<tr>
<td>Piave</td>
<td>Italy</td>
<td>3890</td>
<td>132.0</td>
<td>1181</td>
<td>−1.0...−2.0</td>
<td>69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brenta</td>
<td>Italy</td>
<td>1567</td>
<td>71.0</td>
<td>174</td>
<td>−2.5...−5.0</td>
<td>58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trebia</td>
<td>Italy</td>
<td>1070</td>
<td>24.0</td>
<td>116</td>
<td>62</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vara</td>
<td>Italy</td>
<td>572</td>
<td>23.0</td>
<td>62</td>
<td>85</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 rivers</td>
<td>N and Central Italy</td>
<td>572–3899</td>
<td>8–132</td>
<td>53–222</td>
<td>−8...−10</td>
<td>80</td>
<td>Surian et al. (2009a)</td>
<td></td>
</tr>
<tr>
<td>Tagus</td>
<td>Spain</td>
<td>24788</td>
<td>64.0</td>
<td>1181</td>
<td>−1.13...+ 0.86</td>
<td>37</td>
<td>Urbelarrea et al. (2003)</td>
<td></td>
</tr>
<tr>
<td>Jarama</td>
<td>Spain</td>
<td>11597</td>
<td>38.0</td>
<td>28</td>
<td>32</td>
<td>Martin-Vide et al. (2010)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gallego River</td>
<td>Spain</td>
<td>14000</td>
<td>65.0</td>
<td>20</td>
<td>−4...−6 m</td>
<td>34</td>
<td>Winterbottom (2000)</td>
<td></td>
</tr>
<tr>
<td>Tay</td>
<td>Scotland</td>
<td>4690</td>
<td>160.0</td>
<td>34</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tummel</td>
<td>Prut</td>
<td>28463</td>
<td>85.3</td>
<td>631</td>
<td>−1.13...+ 0.86</td>
<td>30</td>
<td>Răduane et al. (2008a)</td>
<td></td>
</tr>
<tr>
<td>Somesu Mic</td>
<td>Romania</td>
<td>3733</td>
<td>22.6</td>
<td>169</td>
<td>−1...−3</td>
<td>30</td>
<td>Persoju (2010)</td>
<td></td>
</tr>
<tr>
<td>Prahova</td>
<td>Romania</td>
<td>3750</td>
<td>8.1</td>
<td>18</td>
<td>−3...−5</td>
<td>56–65</td>
<td>Armas et al. (2012)</td>
<td></td>
</tr>
<tr>
<td>Moldova</td>
<td>Romania</td>
<td>4316</td>
<td>35.3</td>
<td>110</td>
<td>−0.25...+ 2.70</td>
<td>80</td>
<td>1910–2005</td>
<td>Chiriță et al. (2012)</td>
</tr>
<tr>
<td>Siret</td>
<td>Romania</td>
<td>36123</td>
<td>211.0</td>
<td>657</td>
<td>−0.44...+ 2.70</td>
<td>80</td>
<td>1910–2005</td>
<td>This study</td>
</tr>
<tr>
<td>Suceava</td>
<td>Romania</td>
<td>2330</td>
<td>17.1</td>
<td>156</td>
<td>+0.15...−0.70</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bistrița</td>
<td>Romania</td>
<td>6388</td>
<td>62.7</td>
<td>292</td>
<td>−0.50...+ 1.00</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trotus</td>
<td>Romania</td>
<td>4077</td>
<td>34.6</td>
<td>161</td>
<td>+0.60...−1.03</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Putna</td>
<td>Romania</td>
<td>2518</td>
<td>16.1</td>
<td>146</td>
<td>+1.25...−1.00</td>
<td>30</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
the largest sediment yield measured based on the suspended sediment loads in the closing sections of the rivers were in the Carpathian Bend area, i.e., the basins of the Putna, Ramna, Ramnic, and Buzau Rivers (over 2500 t km$^{-2}$ y$^{-1}$).

Regarding the temporal trends in the channel-bed changes, it is noteworthy that channel adjustments such as incision and narrowing began in the early 20th century (Liébault and Piégay, 2002; Surian and Rinaldi, 2003; Zawiejska and Wyzga, 2010), but reports on the occurrence of these processes throughout Europe became more numerous during the past 30–40 years. The most detailed analysis of river changes during the past 100 years was undertaken in Italy (Surian et al., 2009a). The authors were able to delimit three stages: stage I lasting until 1950, stage II between 1950 and the early 1990s, and stage III post-1990. Prior to 1990, channel beds underwent little change in terms of the magnitude of morphological parameters (width and depth of the channel) caused by the lack of a dominant process. However, during the first stage described by the authors, channel narrowing was established as the prevailing process (likely combined with channel-bed incision). During the second stage (–1980–1990), the incision and narrowing rates were augmented. The third stage (the last 15–20 years) was defined by a decrease in the rates of adjustment by incision and narrowing and the onset of a tendency toward restoration of the previous configuration and recovery of the bed level, according to Surian et al. (2009a).

Our observations are congruent with the pattern proposed by Surian et al. (2009a), as it was determined that the most significant changes in channel beds occurred during the 1980–1990 decade in France, Italy, Poland, and Romania. The matter that we have further documented regards the role of the climatic factor versus the anthropogenic factor in controlling these changes. The significant number of reaches considered for this analysis, with various degrees of artificiality, contributes to increasing the level of confidence in the results. Thus, climatic variability has ingrained a general pattern of evolution of the channel beds, over which human influences have left their own strong mark. The variable that acted as arbitrator in this balance was the sediment load. The scale and complexity of the anthropogenic interventions (such as in the case of the Bistrita River downstream from the Izvorul Muntelui Reservoir) have left the river with too few degrees of freedom. Conversely, in the case of the Siret, regardless of the presence of five small cascading dams, the river was granted enough freedom to rebuild its sediment load, mostly not only from its own bed but also from the inputs of the tributaries originating in the Carpathians.

In western Europe, the human impact on rivers has gained some degree of refinement (as rivers are controlled by fine works of art, gravel mining is banned or severely reduced, extensive work has been performed to reduce the inputs of sediment to channel beds, reforestation, etc.). The statement below summarises a general explanation regarding the causality of the current state of rivers: “Channel adjustments were driven mainly by human actions, but the role of large floods was also notable in some cases. Besides the direct effect of channelization on channel morphology, the major effect of human actions was on sediment regime” (Surian et al., 2009a, p. 94).

Romania is far from establishing a sustainable form of human control over rivers (the strongest argument being the pronounced mobilisation of sediments post-1990 when conservation works on slopes and small-sized channels have decreased severely and deforestation is carried on at an alarming pace). Nevertheless, the onset of the ‘globalisation’ phenomenon of morphological changes in river channels is undisputable, at least for 1960 onward (based on the available reliable database that attests to this). Whereas we were able to create a general view of the magnitude of the vertical channel changes, the matter of determining the degree of platform adjustment remains to be addressed. The few studies published so far suggest that the trend is toward narrowing and has been reported as such almost globally, at least throughout Europe.

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References

Bussuică, A., Caiam, M., Cheval, S., Bojariu, R., Boroneant, C., Baciu, M., Dumitrescu, A., 2010. Climate variability and change in Romania. Editura Pro Universitară, Bucharest (228 pp. (in Romanian)).
Dragoș, C., 2006. Rainfall excess in Romania. Editura Academiei Române, București (178 pp. (in Romanian)).
Ichim, I., Batucu, D., Rădoane, M., Duma, D., 1989. River Channel Morphology and Dynamics. Editura tehnica, Bucuresti (408 pp. (in Romanian)).
James, L.A., 1997. Channel incision on the lower American River, California, from
Kis, T., Blank, V., 2012. River channel response to climate–human–induced hydrologi-
cal changes: Case study on the meandering Hnerad River, Hungary. Geomorphology
175–176, 115–125.
In: Kajak, Z. (Ed.), Ekologiczne podstawy zagospodarowania Wadis i jej dorzecz.
PWN, Warszawa&Oz, pp. 97–108.
Geografiska Annaler 69 A, 221–226.
Korpan, J., 2007. The influence of river training on mountain channel changes (Polish
Li, L., Lu, X., Chen, Z., 2007. River channel change during the last 50 years in the middle
Yangtze River, the Jianli reach. Geomorphology 85, 185–196.
Rinaldi, M., 2003. Recent channel adjustments in alluvial rivers of Tuscany Central Italy.
Rinaldi, M., Surian, M., 2000. Second channel adjustments in the lower Raba River,
Italy. Earth Surface Processes and Landforms 24, 95–108.
Simon, A., Rinaldi, M., 2006. Disturbance, stream incision, and channel evolution: The
roles of excess transport capacity and boundary materials in controlling channel
Staniford, S., 2002. Change in the frequency of extreme events as the indicator of climatic
change in the Holocene (in fluvial systems). Quaternary International 91, 52–32.
Stefan, S., Chiocca, M., Rimbu, N., Baroneanu, C., 2004. Study of meteorological and
hydrological drought in southern Romania from observational data. International
Journal of Climatology 24, 871–881.
Stover, S.C., Montgomery, D.R., 2001. Channel change and flooding, Skolomish River,
Surian, N., 1999. Channel changes due to river regulation: The case of the Piave River,
Italy. Earth Surface Processes and Landforms 24, 1135–1151.
sources in a gravel-bed river, Brenta River, Italy. Earth Surface Processes and Landforms
32, 1641–1856.
Surian, N., Rinaldi, M., 2003. Morphological response to river engineering and manage-
ment in alluvial channels in Italy. Geomorphology 50, 307–326.
Surian, N., Rinaldi, M., Pellegrini, L., Audisio, C., Maraga, F., Teruggi, L., Turitto, O., Zilliani, L., 2005a. Channel adjustments in northern and central Italy over the last 200 years. In:
James, L.A., Rathburn, S.L., Whittear, C.R. (Eds.), Management and Restoration of Flu-
vial Systems with Broad Historical Changes and Human Impacts. :: Special Paper 451.
Geological Society of America, Boulder, CO (83-95 pp.).
Surian, N., Zilliani, L., Comiti, F., Lenzi, M.A., Mao, L., 2009a. Channel adjustments and al-
teration of sediment fluxes in gravel-bed rivers of northeastern Italy: Potentials and limitations for channel recovery. River Research and Applications 25, 551–567.
Tveito, O.E., Wegehenkel, Van der Wel, F., Dobesch, H., 2006. The use of geographic in-
fosystem in transport processes and landforms - Final report cost action
Tangus rivers (central Spain) over the past 500 years. Quaternary Science Rev. 22,
Tveito, O.E., Wegehenkel, Van der Wel, F., Dobesch, H., 2006. The use of geographic in-
fosystem in transport processes and landforms - Final report cost action
Tangus rivers (central Spain) over the past 500 years. Quaternary Science Rev. 22,
Fluvial Geomorphology for River Engineering and Management. Wiley, Chichester,
UK (15–45 pp.).
a case study from the Ėgrello River, Spain. Geomorphology 117 (3–4), 261–271.
Mihalău, D., Briciu, A., 2012. Actual climate evolution in the NE Romania. Manifestations and
Consequences. International Multidisciplinarity 12th Scientific GeoConference: Section
Paige, A.D., Hickin, E.J., 2000. Annual bed-elevation regime in the alluvial channel of
Squamish River, southwestern British Columbia, Canada. Earth Surface Processes
and Landforms 25, 391–1009.
Institutul de Geografia si Geofizica 50, 149–165.
“Gh. Asachi, Iaşi (in Romanian).
Persiou, L., Rădoane, M., 2011. Spatial and temporal controls on historical channel
responses - study of an atypical case: Someşu Mic River, Romania. Earth Surface
Landforms and Processes 36 (10), 1391–1409.
Pêlish, P., 2002. Channel evolution of the pre-channelised Danube River in Bratislava,
to human impact in the southern Blue Ridge Mountains, USA. Geomorphology 78,
142–160.
Rădoane, M., Rădoane, N., 2005. Dams, sediment sources and reservoir silting in
Rădoane, M., Rădoane, N., Dumitriu, D., 2003. Geomorphological evolution of longitudi-
Rădoane, M., Rădoane, N., Oprea-Canceviu, D., 2008a. Contemporary changes of the
Rădoane, M., Rădoane, N., Dumitriu, D., Miclus, M., 2008b. Downstream variation in
bed sediment size along the east Carpathian rivers: Evidence of the role of sedi-
ment sources. Earth Surface Landforms and Processes 32, 674–694.
Rădoane, M., Rădoane, N., Cristea, I., Persiou, I., Burdudea, A., 2008c. Quantitative analy-
sis in the fluvial geomorphology. Geographia Tecnica 1, 100–111.
Rădoane, M., Pandi, G., Rădoane, N., 2010. Contemporary bed elevation changes from
the Eastern Carpathians. Carpathian Journal of Earth and Environmental Sciences
5, 49–60.
D.R., Vietek, J.D. (Eds.), Thresholds in Geomorphology. Allen and Unwin, London
(179-208 pp.).
Rinaldi, M., 2003. Recent channel adjustments in alluvial rivers of Tuscany Central Italy.
Geomorphology 22, 57–71.