



The influence of river training on channel changes during the 20th century in the Lower Siret River (Romania)

L'influence des aménagements sur la métamorphose fluviale du Siret inférieur (Roumanie) au XX^e siècle

Florence Salit^a, Gilles Arnaud-Fassetta^b, Liliana Zaharia^c, Malika Madelin^b, Gérard Beltrando^b

^a Université de Cergy-Pontoise – UMR 8586 du CNRS (PRODIG) – 75205 Paris cedex 13 – France.

^b Université Paris-Diderot-Sorbonne-Paris-Cité – UMR 8586 du CNRS (PRODIG) – 75205 Paris cedex 13 – France.

^c Faculty of Geography – University of Bucharest – Bd Bălcescu N°1, Secteur 1 – 010041 Bucharest – Romania.

Abstract

This study provides an example of a river affected by water management strategy during the 20th century. This work focuses on the last tributary of the Danube River, the Lower Siret River (130 km length; mean annual discharge: 210 m³/s), located east of the Carpathians. The aim of this paper is to determine the morphological changes of the Lower Siret River (Romania) from 1891 to 2010, and to define (i) the cause of morphological adjustments and (ii) the impact of engineering works. The evolution of the Lower Siret River during the 20th century was analysed on the basis of historical sources (text and maps), records of human intervention in the catchment, and climatic and hydrological data. By using statistical and GIS analysis, hydro-morphological changes were calculated and the respective impact of driving factors (climate, land use, engineering works) was discussed. In the Lower Siret River, morphological adjustments, especially active-channel narrowing (- 46 % between 1940 and 2010) and simplification of channel pattern, can be explained by engineering interventions especially in the 1970s rather than just climatic variability.

Keywords: morphological changes, engineering works, channel narrowing, Lower Siret River, Romania.

Résumé

Cette étude s'attache à analyser la dynamique fluviale sur un siècle d'un cours d'eau fortement anthropisé, en lien avec les politiques d'aménagement et la variabilité climatique. Ce travail se concentre sur le secteur inférieur du Siret, avant dernier affluent du Danube (130 km de long et débit moyen annuel de 210 m³/s à la station de Lungoci). L'objectif de cet article est 1) de déterminer et d'analyser les modifications morphologiques du Siret inférieur du début du XX^e siècle à 2010 et 2) d'en déterminer les principales causes. L'étude se fonde sur l'analyse de données historiques (textes et cartes), des données hydrologiques et climatiques et l'historique de l'aménagement de la rivière. À partir d'une analyse statistique et de la création d'un SIG, les évolutions hydro-morphologiques ont été quantifiées et la part de chacun des facteurs explicatifs (climat, occupation du sol, aménagements) discutés. Les principaux résultats montrent une contraction majeure de la bande active (- 46 % de 1940 à 2010) et une simplification du style fluvial particulièrement après 1970. Ces modifications sont expliquées avant tout par les stratégies d'aménagement de lutte contre les inondations (chenalisation, reboisement des berges et barrages) plutôt que par la variabilité climatique.

Mots clés : changements morphologiques, aménagements, contraction de la bande active, Siret inférieur, Roumanie.

Version française abrégée

La description et l'analyse des changements historiques dans les systèmes fluviaux anthropisés ont mobilisé de nombreux chercheurs. Une tendance générale à l'incision des rivières a été observée, aboutissant à un rétrécissement du lit depuis 150 ans dans de nombreuses rivières européennes (Liébault et Piégay, 2002 ; Surian et Rinaldi, 2003 ; Wyżga, 2008). Un débat est né de ce constat entre les tenants d'une origine anthropique de ces changements et les tenants d'une origine plus naturelle. L'objectif de cet article est de déterminer et d'analyser 1) les dynamiques hydrologiques et morphologiques décelables sur le Siret inférieur (Roumanie) du début du XX^e siècle à 2010 et 2) quels facteurs peuvent intervenir pour expliquer ces variations.

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*Auteur correspondant, Tél. : 33 (0)1 34 25 64 09 ; Fax : 33 (0)1 44 07 75 63

Courriels : florence.salit@u-cergy.fr (Florence Salit)

gilles.arnaud-fassetta@univ-paris-diderot.fr (Gilles Arnaud-Fassetta)

zaharia.lili@hotmail.com (Liliana Zaharia)

malika.madelin@univ-paris-diderot.fr (Malika Madelin)

beltrando@univ-paris-diderot.fr (Gérard Beltrando)

La première partie de l'article présente le site d'étude du Siret inférieur (fig. 1) ainsi que le contexte particulier de l'aménagement des cours d'eau en Roumanie. Le bassin du Siret, le plus grand de Roumanie, est situé à l'est des Carpates. Avec un débit moyen de 210 m³/s à la station de Lungoci, le Siret est l'avant dernier affluent majeur du Danu-

be. Le Siret a fait l'objet d'un aménagement intensif (900 km de digues) particulièrement après l'inondation majeure de 1970 (tab. 1).

La seconde partie de l'article s'attache à décrire les données et méthodes utilisées, afin de définir les variations hydrologiques et morphologiques du Siret inférieur. Les données hydrologiques utilisées sont des séries chronologiques de débit – liquide et matières en suspension (MES) – à la station de Lungoci. Un test de tendance (Mann-Kendall) et deux tests de rupture ont été appliqués pour détecter une singularité unique (Pettitt) ou multiple (Hubert) à toutes les séries de données. L'analyse diachronique des dynamiques en plan du Siret a été réalisée à partir des données spatiales de 1940, 1981 et 2010, digitalisées, intégrées et analysées dans un SIG. Le secteur a été découpé en quatre tronçons homogènes et dix sous-tronçons (fig. 1). Quatre indices ont été calculés : la longueur du chenal, la largeur de la bande active, l'indice de tressage et l'indice de sinuosité.

La troisième partie présente les différents résultats des analyses hydrologique et morphologique. On constate une diminution de 46 % de la largeur de la bande active de 1940 à 2010 sur l'ensemble du secteur (fig. 2). La majorité (81 %) de cette réduction se déroule entre 1940 et 1981. Ces tendances masquent les différentes évolutions au sein du secteur. Associés à une contraction majeure de la bande active, les deux premiers tronçons connaissent une simplification de leur style fluvial, qui passe d'un style en tresses à rectiligne, surtout à partir de 1970 (fig. 3). Trois phases ont été identifiées dans l'analyse hydrologique (fig. 4) : 1) 1951/53-1968 : des débits faibles et donc des crues peu nombreuses ; 2) 1968-1984 : des débits liquides et d'alluvions en suspension moyens et maximaux importants ; 3) 1985-2010/11 : forte variabilité des débits liquides. Les crues sont moins fréquentes que lors de la période précédente mais plus intenses. Les débits de MES connaissent une baisse majeure surtout à partir de 1991.

La quatrième partie met en avant les causes de ces différentes évolutions constatées. Plusieurs facteurs explicatifs sont analysés : les facteurs climatiques, les changements d'occupation du sol, plus particulièrement l'évolution des surfaces boisées, et les aménagements dont les barrages et les digues. Chacun de ces facteurs peut avoir une action combinée dans le système fluvial (Gregory, 2006) ou même avoir des effets qui s'annulent. L'analyse des cumuls de précipitations montre que les débits plus faibles des années 1950 et 1960 tout comme la hausse des débits constatée dans les années 1970 jusqu'au milieu des années 1980 s'expliquent en partie par le régime des précipitations. Ainsi, les premiers résultats obtenus suggèrent que le rétrécissement de la bande active constaté dans les années 1970-80 ne peut être lié à une période de crues moins intenses ou moins fréquentes puisque cette période correspond à une hausse moyenne des débits en lien avec une augmentation des précipitations. Les phases de variations des débits liquides tout comme la période de contraction de la bande active ne correspondent pas aux années de mise en place des barrages (1977-1992) ; ces derniers ne semblent être que des facteurs aggravants du phénomène. La chenalisation et plus particu-

lièrement les travaux de régularisation effectués sur le Siret apparaissent comme l'une des causes principales de la contraction de la bande active. Plusieurs éléments en témoignent : 1) la concordance entre période de contraction de la bande active et période d'aménagement intensif et 2) la réduction brusque en un ou deux ans de la largeur de la bande active, notamment pour les TRI.2 et TRI.3 (fig. 5).

Les variations spatiales (entre les tronçons) et temporelles (sur environ un siècle) des ajustements du chenal ne permettent pas d'apporter une réponse unique aux différentes évolutions constatées. La figure 7 présente la synthèse des causes possibles et du poids de chacune dans l'évolution de la largeur de la bande active du Siret inférieur de 1900 à 2010, avec une attention particulière accordée à la période 1970-1980. Plusieurs périodes sont distinguées : 1) 1900-1950 : le climat et le couvert forestier sont considérés comme des facteurs explicatifs majeurs dans l'élargissement de la bande active car aucun aménagement n'est présent lors de cette période ; 2) 1950-1969 : le ralentissement de l'élargissement de la bande active à partir des années 50 n'est qu'une hypothèse : la baisse des cumuls pluviométriques, qui se traduisent par une baisse des débits moyens annuels, peut conduire au ralentissement de l'élargissement ; 3) 1970-1983 : la chenalisation massive combinée aux mesures intensives de reboisement des corridors fluviaux favorisent une contraction de la bande active et un accroissement des vitesses d'écoulement. Les conditions climatiques (forts cumuls pluviométriques annuels conduisant à de nombreuses crues) n'ont pas pu jouer un rôle dans cette tendance. Au contraire, elles auraient plutôt eu un rôle inverse en favorisant la mise en place des politiques d'aménagement. Mis en service à la fin de cette période seulement, les barrages n'ont fait qu'accentuer cette tendance ; 4) 1984-1991 : les barrages associés au maintien de l'endiguement ont accentué la réduction de la bande active ; 5) 1992-2010 : la chenalisation a favorisé la stabilité de la bande active. Les conditions climatiques, même si elles sont très variables (événements hydro-climatiques intenses sur la période), ne peuvent jouer sur ce marqueur, le lit étant contraint dans un réseau de digues.

Le Siret inférieur est un exemple de rivière fortement anthropisée dont les caractéristiques morphologiques actuelles sont très influencées par la vague d'aménagements des années 1970. Les politiques passées de gestion de la rivière ont modifié le comportement du système fluvial et, en ce sens, les nouvelles stratégies de gestion des inondations doivent intégrer ces nouvelles caractéristiques hydrogéomorphologiques pour une meilleure appréhension des interactions Homme-Environnement.

1. Introduction

Throughout Europe, many rivers have undergone widespread channel adjustments since the beginning of the 20th century, in particular incision and narrowing (Petts et al., 1989). The origin of these adjustments is widely discussed in the scientific community, due to the cumulative impact of both natural and human driven factors on fluvial system (Downs et al., 2013). Many authors (Bravard et al., 1997;



Surian, 1999; Winterbottom, 2000; Liébault and Piégay, 2001, 2002; Arnaud-Fassetta, 2003; Swanson et al., 2011; Armaş et al., 2012; Ziliani and Surian, 2012; Siché and Arnaud-Fassetta, 2014) showed that, since the 19th century, human interventions such as dams, channelisation, in-stream mining, flow diversion, and land-use changes have affected the variables (water and sediment discharges; Schumm, 1977) controlling the hydromorphology of rivers. Each human intervention affects these variables in a different way and their effects may be cumulative but could also offset each other. The gravel mining led to a decrease of sediment whereas flow diversion involved a decrease of channel flow. Dams impose different changes of variables of control that depend on the decreasing peak runoff and sediment loads (Petts and Gurnell, 2005). These changes led to a complex response of channel adjustment. The decrease of sediment supply could lead to the narrowing and the incision of the riverbed and increased the disconnection between the channels and their alluvial plains (Gurnell, 1995). Some of authors (Liébault and Piégay, 2002; Wyżga, 2008) showed that there was no clear evidence that in the last decades, the climate could be regarded as the major factor of these morphological evolutions. Other authors (Pisút, 2002; Uribelarrea et al., 2003; Rădoane et al., 2010; Rădoane et al., 2013) have shown that climate change and associated changes in floods frequency and magnitude are the most important factor influencing morphological dynamics. Human interventions would only have accentuated these trends created by climate.

The Romanian rivers have known the same trend. Both riverbed incision and channel narrowing were documented by several authors (Rădoane et al., 2010; Persoiu and Rădoane, 2011; Armaş et al., 2012; Rădoane et al., 2013) but the origins of these adjustments are still widely discussed. In Romania, the context of engineering works in the riverbeds and floodplains is quite particular: an intense phase of river arrangement took place from the 1970s decade until the 1990s. Before this phase the engineering works (such as dyke) were very localised and specific. Today, the water management strategy goes through a transitional period between the needs of the economy (in-stream mining or water supply) and the implementation of the EU Water Framework Directive and Flood Directive. One of the aims of these directives is to implement an integrative management of water resource and flood at catchment scale (*i.e.* consider downstream effects on any riverbeds projects) and to preserve or/and restore good quality of water bodies.

The aim of this paper is to determine and analyse the morphological changes of the Lower Siret River (Romania) in a diachronic way from the beginning of the

20th century to 2010, in order (i) to define the hydro-morphological changes of the river and (ii) to investigate the causes of these changes and especially the impact of engineering works. Our final goal is to assess the impact of the past management strategy on the Lower Siret River in the frame of a future implementation of a new EU River strategy.

2. Field context and engineering history

The Siret river basin, located east of the Carpathians, has the largest catchment of the country with a total area of 42,900 km² and is one of the last tributaries of the Danube River. The mean annual flow is 210 m³/s at the Lungoci station (situated 88 km upstream of the Danube confluence). The largest part of the basin (48%) belongs to the Moldavian platform, made up of marls, sands, sandstones, gravel, and limestone (Rădoane et al., 2013). The basin morphology varies between a relatively deep valley upstream with a mean slope of 2%, and a plane morphology downstream, with a slope of less than 0.2% (Ministerul Mediului, 2009). The area covered with forests represents 37% of the basin surface (based upon Corine Land Cover data in 2006). The Siret catchment includes 291 dams and reservoirs built between the 1950s and 2007 for hydropower energy, irrigation, water supply, flood control, and fishing. Only seven reservoirs, designed to provide hydroelectric power and to flood control, are located in the Siret River. Just one dam (Movileni), achieved in 2007 is located on the Lower Siret River (fig. 1B).

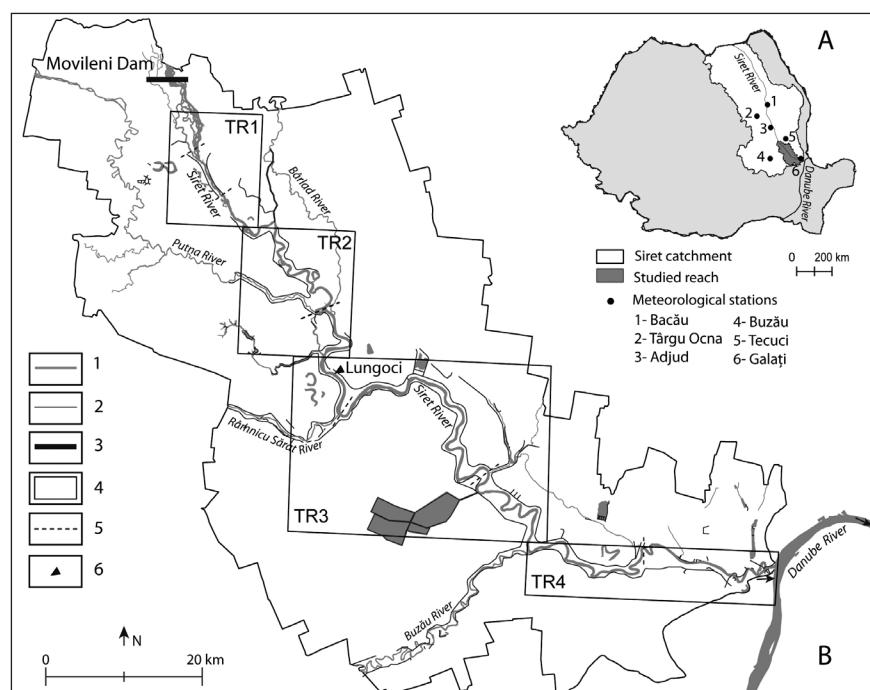


Fig. 1 – Studied reaches in the Siret catchment. A: Location of TR1 to TR4 reaches selected for the morphological study and engineering works. B: Study areas; 1: river and lake; 2: dyke; 3: dam; 4: reaches; 5: sub-reaches; 6: hydrometric station.

Fig. 1 – Localisation de la zone d'étude dans le bassin du Siret. A : Localisation des TR1 à TR4 sélectionnés pour l'analyse morphologique et localisation des aménagements. B : Zones d'étude 1 : rivière et lac ; 2 : digue ; 3 : barrage ; 4 : tronçon ; 5 : sous-tronçon ; 6 : station hydrométrique.

The study area is a 140-km long river reach located on the lower part of the catchment (fig. 1A). The elevation is between 60 m and 3 m a.s.l. The main tributaries are the Putna River, the Râmmicu Sărat River, the Buzău River and the Bârlad River. The Lower Siret River has a sandy bed with a slope of 0.02%. The majority of the land use is covered by arable lands whereas the forest cover represents almost 6% of the studied sector but only less than 5% of the total forest cover in the whole catchment.

The study area was divided into four reaches (fig. 1B) depending on local, hydrographical (tributaries) and anthropogenic (engineering works, bridges) context, and on available historic maps. The first reach (TR1) is the well documented with eight maps and satellite images from AD 1891 to 2010. Its course has the highest slope (0.07%) and its channel is braided. This reach can be divided into three sub-reaches: the upper one (TR1.1) extends from Movileni dam to the beginning of the levees area (6.5 km); the median one (TR1.2) is constrained by levees for flood control and bank protection structures (4.75 km); the lower one (TR1.3 – 5.25 km) goes from the Siret bridge to the end of the oldest map (1891). The second reach (TR2) is 28-km long and includes three major confluences, which two of them (Putna River and Bârlad River) were modified in the 1970s by deviation and regulation. The river dynamics is constrained by levees for flood control, which impose a channel width of about 200-500 m. TR2 is divided into two sub-reaches depending on tributaries. The third reach (TR3), 60-km long, is characterised by a river channel constrained for a long time (before 1940) by levees. It is divided into three sub-reaches depending on tributaries, and fluvial pattern is meandering. Downstream, the fourth reach (TR4 –

37.5 km) has the lowest slope (0.01%) and is divided into two sub-reaches constrained by levees.

Engineering control works are various in the Lower Siret River and they are designed to control the river dynamics and to mitigate the fluvial risk linked to flood hazard and bank erosion. Water management strategy in the catchment stems from three phases (from i to iii), which implementation can be explained by both political (kind of government) and following the occurrence of major floods (tab. 1). (i) Between 1940 and the end of the 1960s, the floodplain was seen as a resource for the exploitation of the water and the land. (ii) In 1970, a major flood event occurred (a 10-year flood with a peak discharge of 3186 m³/s at Lungoci station), which led to change the river management strategy. The river was more a danger for both population and economy. Consequently, a complete and systematic arrangement was implemented with 900 km of dykes in the whole area, flow diversion, regulation, and an extensive afforestation policy. (iii) In July 2005, the Lower Siret River experienced a 100-year flood with a peak discharge of 4650 m³/s, highest value recorded at the Lungoci station (fig. 1B). This hydrological event was catastrophic, causing 23 deaths and billions Euros of damages (Ministerul Mediului și Gospodăririi Apelor, 2006). Moreover this flood highlighted the defects of structural measures (several breaches appeared) and locally, network of dykes are severely discussed. Nowadays, the floodplain is considered as a complex area between natural heritage and danger. The Lower Siret River is a European protected area for birds and wetlands, but it is also a resource (water and sediment supply) for the new direction of the Romanian's economy. The Lower Siret River has experienced a quite long history a

Phases	Perception of the river	Strategy	Human interventions	Engineering works in the studied reach
1940-1969	Resource	Restricted	Sanitation drainage	15,000 ha
			Channelisation	133 km
Flood	1970			
1970-2000	Danger	Complete and systematic	Channelisation	900 km levees
			Dams reservoirs	6 (upstream reach 1977-92)
			Regulation	7 CC* 24 G* 2CD*
			Afforestation	+71 km ²
			Bank protection	20 km
Flood	2005			
2005-2012	Danger	Integrated	Dam reservoir	1 (2007)
	Resource		In-stream mining	1,384,644 m ³ /a allowed**
	Natural Heritage		Banks protection	15 km + 5G*

*CC: channel cut off; G: groynes; CD: channel diversion.

** estimation for 7 gravel-mining operations.

Tab. 1 – Evolution of the management strategies from 1940 to 2012 in the Lower Siret River. Data derived from thirty different sources among which official reports, historical engineering works, literature, and field survey.

Tab. 1 – Évolution des stratégies d'aménagement de 1940 à 2012 sur le Siret inférieur. Données issues de trente différentes sources parmi lesquelles des rapports officiels, l'historique des travaux d'aménagement, la littérature et des observations de terrain.



human intervention and the aim of this work is to determine the consequences on its morphology.

3. Data and methods

The evolution of the Lower Siret River during the 20th century was analysed on the basis of historical sources (text and maps), records of human intervention in the catchment, and hydrological data in order to assess planar changes of the River. The choice was made to study only the planar evolution as a first step to then analyse the morphological changes of the Siret River.

3.1. Analysis of cartographic sources

In order to get comparable morphological data and analyse the Lower Siret River plan view dynamics, data were digitised from three cartographic materials, the only ones available for the entire reach (1940, 1981, and 2010). The use of historical sources such as maps (Piégay and Schumm, 2003; Hohensinner et al., 2004; Zanoni et al., 2008; Michalkova et al., 2011) are essential to understand the nature and magnitude of river channels modifications. Changes in the Lower Siret channel were accounted through diachronic analysis interpreting historic maps. Unfortunately no cartographic material was available in the timing of flood event. The planform morphology of the studied reach was documented by (i) 1:20,000 scale historic map sheets called *Planuri Directoare de Tragere* from 1891 to 1940; (ii) 1:25,000 scale Romanian topographic maps from 1981; (iii) and Google Earth images from 2009 and 2010. All digital data were captured in Quantum GIS environment projected into Google Mercator. We can estimate a potential error in results of +/- 10 m due to differences in quality of sources and digitalisation. In order to be more accurate in the timing of morphological changes, a set of topographic maps (1970, 1971, and 1990) and orthophotoplans (2005), available only for TR1 and TR2 were qualitatively used. The small scale (more than 1:50,000) of these maps did not allow a quantification of channel change. Furthermore, geomorphological indicators were selected to assess the spatial-temporal modifications of the channel. These indicators are the mean channel length, the braided index (average number of anabranches perpendicular to the bed axis; Ashmore, 1991), the sinuosity index (*SI*), and the mean active-channel width (channel + alluvial bars). The various channel morphologies were grouped into four general types indicated by the *SI* (Leopold et al., 1964): *SI* < 1.05, single-thread; 1.05 < *SI* < 1.25, sinuous; 1.25 < *SI* < 1.5, very sinuous; *SI* > 1.5, meandering. The active-channel width was automatically measured in 546 transects located along the Lower Siret River each 250 m. The evolution of the land-use cover of studied area was measured on the mapping materials and Corine Land Cover from 2006. Only riparian forest was measured in this analysis due to its relevant hydromorphological role in the evolution of channel planform (Gurnell, 1995). The GIS construction was useful to quantify both channel changes and forest cover evolution. Number and state of present engineering works were listed by several field surveys from 2009 to 2012.

3.2. Analysis of hydroclimatic data

The hydroclimatic analysis was performed using two kinds of data. First, in order to define temporal tendencies of precipitation, the annual cumulative precipitation of six meteorological stations implemented in the Siret catchment was used (fig 1A). Produced by the National Administration of Meteorology (ANM), the data cover the period 1961-2010. These data are the only available in the Siret catchment with no gap for that period of time. Then, hydrological analysis derived from a data series allowed us to identify temporal tendencies. Flow records from the stream-gauging station in Lungoci were used (fig 1B). Data series included daily average water discharges from which mean annual water discharge was calculated (Q_{mean} ; 1953-2010), maximum annual water discharge (Q_{max} ; 1951-2011), daily average suspended-sediment discharge ($Q_{\text{s mean}}$; 1971-2011) from which mean annual suspended-sediment discharge was calculated, and maximum annual suspended-sediment discharge ($Q_{\text{s max}}$; 1971-2011). Time series were measured by ANAR (Administrația Națională Apele Române – “Romania Waters” National Administration Siret Water Branch) and obtained from ANAR and from GRDC (Global Runoff Data Center). After a critical analysis of data sets, temporal variations were analysed using three complementary statistical methods: (i) the non-parametric Mann-Kendall test (Kendall, 1975) was used to test the independence of the consecutive elements of an equally spaced time series. The null hypothesis is H_0 : the series is random, and its alternative is H_1 : there is a trend in the series. The significance level was measured by the probability $p < 0.01$. (ii) The break test of Pettitt (1979) was performed to detect changes in the mean of the time series. The change-point called break point provides here the year where the mean changes in time series. The Pettitt test is a non-parametric test. The null hypothesis is that there is no break point in the discharge series. The significance level chosen is $p < 0.01$. (iii) The Hubert’s segmentation procedure (Hubert et al., 1989) was applied to detect multiple breaks in the time series. The principle is to cut the series into n segments ($n > 1$) such that the calculated means of the neighbouring sub-series significantly differ. To limit the segmentation, the means of two contiguous segments must be different to the point of satisfying Scheffé’s test. Moreover if the phase described by the test is under five years, the result is not considered relevant. The procedure gives the timing of the breaks. The test was applied automatically with Khronestat 1.01.

4. Results

4.1. Changes in channel planform

The results of the morphologic analysis (fig. 2) show two noticeable evolutions over time: an overall narrowing and a simplification of channel form.

On the Lower Siret River, the mean of channel widths decreased from 670 m in 1940 to 300 m in 2010. The channel rapidly narrowed (7 m/a) between 1940 and 1981 but the



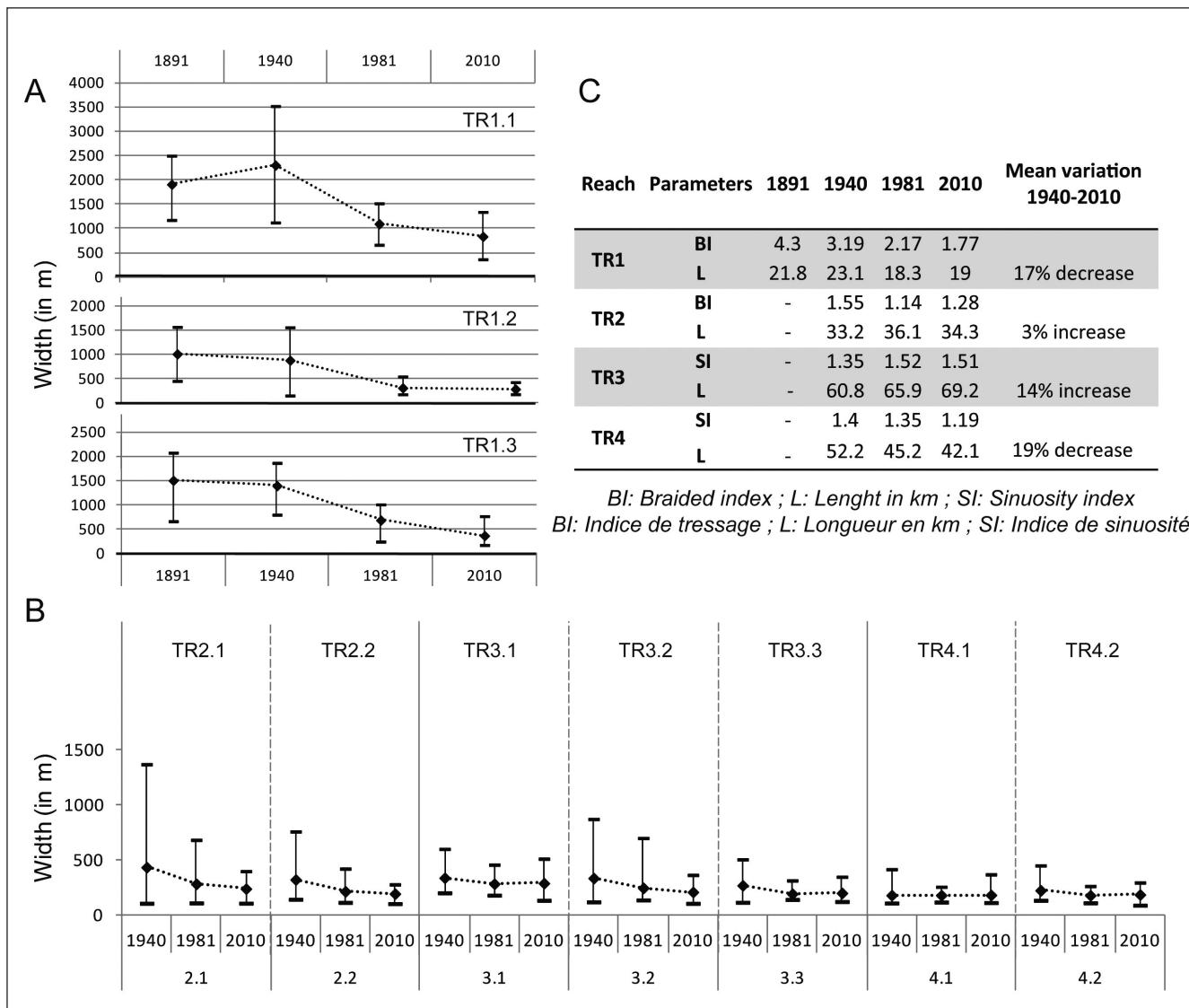


Fig. 2 – Changes in channel planform in the Lower Siret River from 1891 to 2010. Active channel width variations for TR1 (A) and for TR2, TR3 and TR4 (B); C: Geomorphological indicators variations on TR1, TR2, TR3 and TR4 (SI: sinuosity index; BI: braided index; L: channel length in km).

Fig. 2 – Évolution de la morphologie en plan du Siret inférieur de 1891 à 2010. Variations de la largeur de la bande active sur le TR1 (A) et sur les TR2, TR3 et TR4 (B) ; C : Variations des indicateurs géomorphologiques sur les TR1, TR2, TR3 et TR4 (SI : indice de sinuosité ; BI : indice de tressage ; L : longueur du chenal en km).

narrowing fell (2.4 m/a) between 1981 and 2010. Eighty-one percent of the narrowing occurred between 1940 and 1981 for the all area. Figure 2 shows the main results for each studied reach. The first reach (TR1) recorded the most accentuated and complex changes (fig. 2A): the mean active-channel width increased (+ 395 m) from 1891 to 1940, in the first sub-reach (TR1.1) whereas the mean active-channel greatly decreased (- 1467 m) from 1940 to 2010. TR1.2 and TR1.3 recorded another trend: the decrease of the mean active-channel is slight from 1891 to 1940 (respectively - 130 and - 109 m) and more accentuated from 1940 to 2010 (respectively - 592 and - 1028 m). The mean active-channel width generally decreased from 1940 to 1981 in the TR2 and TR3 (fig. 2B) even if the decrease is more pronounced in TR2. The mean active channel width remains

almost the same for the last reach (TR4). Finally from 1981 to 2010 the active channel width slightly decreased in TR2 and TR3.2 but slightly increased in TR3.1 and TR3.3 TR4.

The simplification of the channel pattern (fig. 2C) is first recorded by the decrease of the braided index in the two first reaches from 1940 to 2010 (- 1.42 and - 0.27 respectively) and then by the decrease of channel length (-10 km) in TR4 due to six cut-off meanders from 1940 to 2010. The change was limited on the third reach (TR3); only the sinuosity index increased in 1981 from very sinuous to meandering. It appears that the two last reaches (TR3 and TR4) recorded the less change over time.

In order to provide more details for the narrowing and simplification period, we use a set of available data existing only for the two first reaches (TR1 and TR2). The maps of

1970, 1971 and 1990 integrated into the GIS allowed a comparison of the channel but did not allow a quantitative analysis of channel narrowing (because of the scale and the low quality of the maps). Narrowing produced a significant change in the channel pattern, from braided to single-thread especially on the TR1. Channel narrowing began between 1940 and 1970 but the majority of the decrease took place between 1970 and 1981 (fig. 3). The TR1.1 shows the most complex evolution: an avulsion occurred before 1981 and the numbers of anabranches greatly decreased between 1970 and 1971. These evolutions might be explained by a major flood in 1970 ($3186 \text{ m}^3/\text{s}$ at Lungoci station). The pattern evolution is accentuated from 1990 to 2010 by the completion of the Movileni dam in 2007, even if we can notice a channel widening between 2005 and 2010. The evolution of the TR2.1 follows the same trend even if the variations (simplification of the channel pattern, cut-off meander; narrowing) are less accentuated. To conclude, the active channel on the TR1 and TR2.1 narrowed and the channel pattern in TR1.1 and TR1.2 changed from braided to single-thread between 1940 and 1981, especially from 1970.

4.2. Changes in discharge and suspended-sediment dynamics

The Mann-Kendall test does not support the existence of significant change in time ($p < 0.01$) for mean annual discharge and maximum annual discharge (tab. 2). The proba-

bility to reject the null hypothesis when it is true is high (45%), thus there is no trend in the time series. Nevertheless, the results of Pettitt test at the significance level ($p < 0.01$) show that there is a significant break point in the year 1968. The Hubert's segmentation was applied in order to confirm this result. There is no significant break point in the maximum annual discharge because the period found by the test is under five years long. But two dates seem to be especially significant in the mean annual discharge: 1968 and 1984. The results of Mann-Kendall tests for suspended-sediment discharges (Q_s) denote that the null hypothesis is rejected, so the series have a trend. Two phases appear in the time series with a break point in 1984 for the mean annual sediment discharge. Nevertheless, the break point is different and more significant for the maximum annual sediment discharge, with a decrease of the mean of 80%. The hydrological analysis lead to the definition of three phases (fig. 4): (i) 1953-1968: low mean annual and maximum annual Q ; (ii) 1968-1984: high mean annual and maximum annual discharges (Q and Q_s); (iii) 1984-2010: high variability of Q , denoted by standard variation and strong decreases of Q_s especially after 1992.

5. Cause of channel changes

Channel geometry adjusts over time in response to changes that affect water and sediment discharges. The causes of control-variables changes are multiple and complex. Climatic

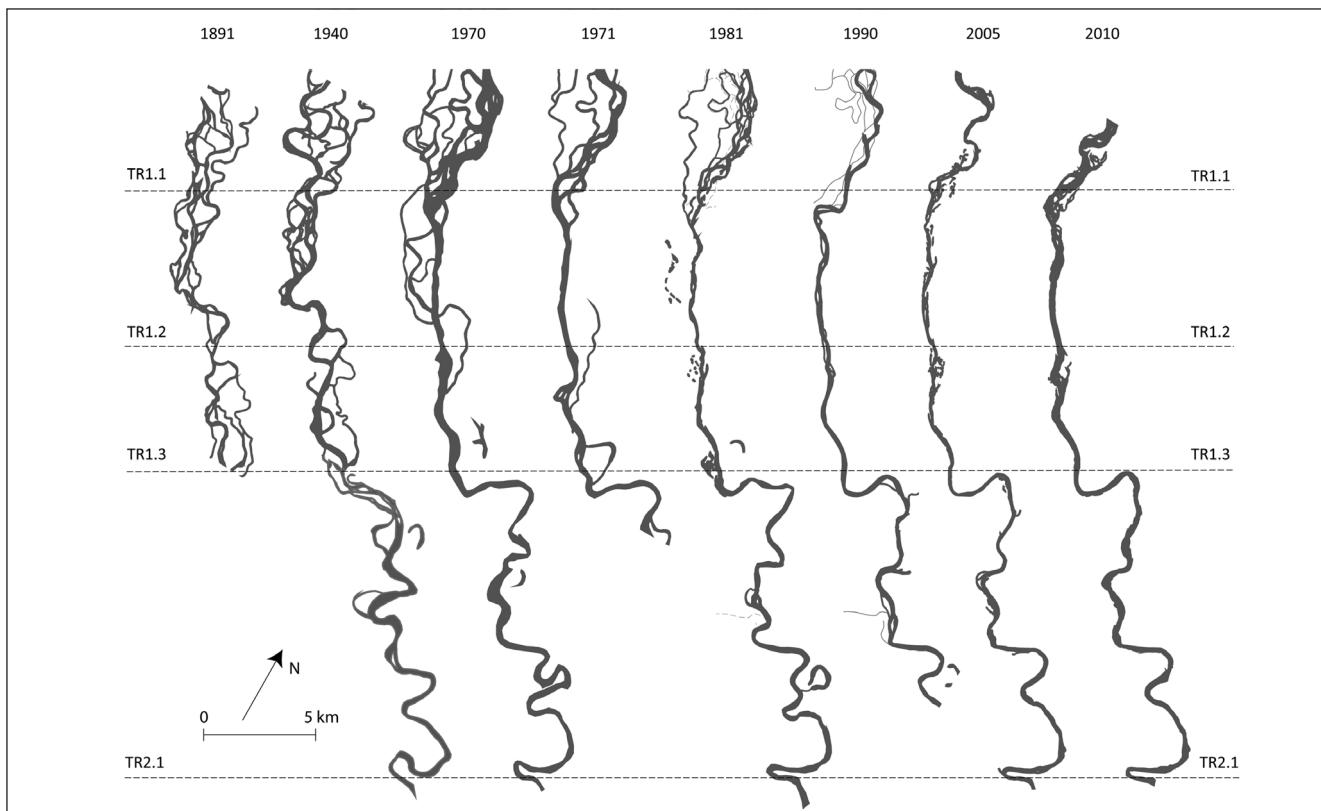


Fig. 3 – Channel narrowing of the Lower Siret River (TR1-TR2 reaches) from 1891 to 2010.

Fig. 3 – Contraction de la bande active du Siret inférieur (TR1 et TR2) de 1891 à 2010.

Variables	Time	Mann-Kendall test*	Pettitt test *	Break point	Hubert segmentation	Mean	Standard deviation
Q_{mean}	1953-2010 (57 years)	45.25	12.1	1968	1953-1967	160.5	45.1
					1968 -1983	267.9	56.7
					1984 -2009	196.2	86.6
Q_{max}	1951-2011 (60 years)	48.19	5.43	1968	-	-	-
$Q_{s mean}$	1971-2011 (40 years)	<0.01	<0.01	1985	1971-1983	454.3	132.5
					1984 -2011	123.6	159.25
$Q_{s max}$	1971-2011 (40 years)	<0.01	<0.01	1991	1971-1991	15000	13326.2
					1992 -2011	2512.6	3600.8

* Probability of correctly rejecting the null hypothesis (H_0) when it is truth. Significant level $p=0.01$ in %.

Tab. 2 – Results of the statistical tests on mean and maximum water (Q_{mean} and Q_{max}) and suspended-sediment ($Q_{s mean}$ and $Q_{s max}$) discharges of the Lower Siret River at Lungoci station. Italic: no significant break point; bold: break point. Data: ANAR-Siret Water Branch, GRDC.

Tab. 2 – Résultats des tests statistiques sur les débits liquides moyens et maximaux (Q_{mean} et Q_{max}) et sur les débits d'alluvions en suspension ($Q_{s mean}$ et $Q_{s max}$) à la station de Lungoci sur le Siret inférieur. En italique : absence de point de rupture significatif ; en gras : point de rupture. Source des données : ANAR- Organisme du Siret, GRDC.

changes since the end of Little Ice Age associated with the human interventions such as dams, flow regulation, channelisation and in-stream gravel mining are cited as the main causes of channel changes (Bravard et al., 1997; Winterbottom, 2000). Increase of the precipitation induces directly the increase of water discharge. Dams and reservoirs reduce the sediment load downstream and the peak flow discharge (Petts and Gurnell, 2005). Flow regulation and embankment can induce the narrowing of the active channel and the reduction of braided index (Surian, 1999). The extent of riparian forest tends to fix the channel and reduce the sediment supply. All these causes can be coincident (Gregory, 2006) and it is possible to assess the role of each cause involving the narrowing of the active channel.

5.1. The influence of the climatic factor

Most of research on precipitation tendencies in Romania began in the 1960s. It is thus difficult to assess the part of climatic factor before 1960 due to the lack of data (Ştefan et al., 2004; Apostol et al., 2012; Ştefănescu et al., 2013). We only know some hydrological events (1897, 1902, 1914,

1930, 1942) occurring in the Siret River (Mustătea, 2005). These events could induce a widening of the active-channel and explain the trend of the TR1.1 between 1891 and 1940. Nevertheless, we can assess the precipitation tendencies in the

A	Stations	Time	Latitude	Longitude	Elevation (in m)	Mann-Kendall test*	Pettitt test*	Break point
Adjud	1961-2006 (45 years)	46.1°	27.167°	102	66.5%	49.3%	1981	
Bacău	1960-2010 (50 years)	46.533°	26.917°	190	98.7%	24.59%	1984	
Buzău	1945-2010 (65 years)	45.133°	26.85°	97	94.71%	70.88%	1981	
Galați	1961-2010 (49 years)	45.483°	28.033°	72	80.19%	68.56%	1995	
Târgu Ocna	1961-2007 (46 years)	45.85°	27.417°	388	63.54%	56.29%	1972	
Tecuci	1961-2006 (45 years)	47.217°	26.383°	61	81.29%	71.74%	1995	

* Probability of correctly rejecting the null hypothesis (H_0) when it is truth. Significant level $p=0.01$ in %.

B	Years	1891	1940	1971	1981	1990	2006
Area (in km ²)		12.47	13.36	28.14	50.13	24.33	47.62
% compared with the previous period		-	+7.2	+110.6	+78.2	-48.5	+95.7

Tab. 3 – The role of climatic conditions and land-cover use. Main characteristics of meteorological stations in the Siret catchment and results of statistical tests; data ANM. (A) Evolution of the forest in the first reach (TR1) of the Lower Siret River according to topographical maps and (B) CLC 2006.

Tab. 3 – Le rôle des conditions climatiques et de l'occupation du sol. Principales caractéristiques des stations météorologiques sur le bassin versant du Siret et résultats des tests statistiques ; données ANM. (A) Evolution de la forêt sur le premier tronçon (TR1) du Siret inférieur selon les cartes topographiques et (B) Corine Land Cover 2006.



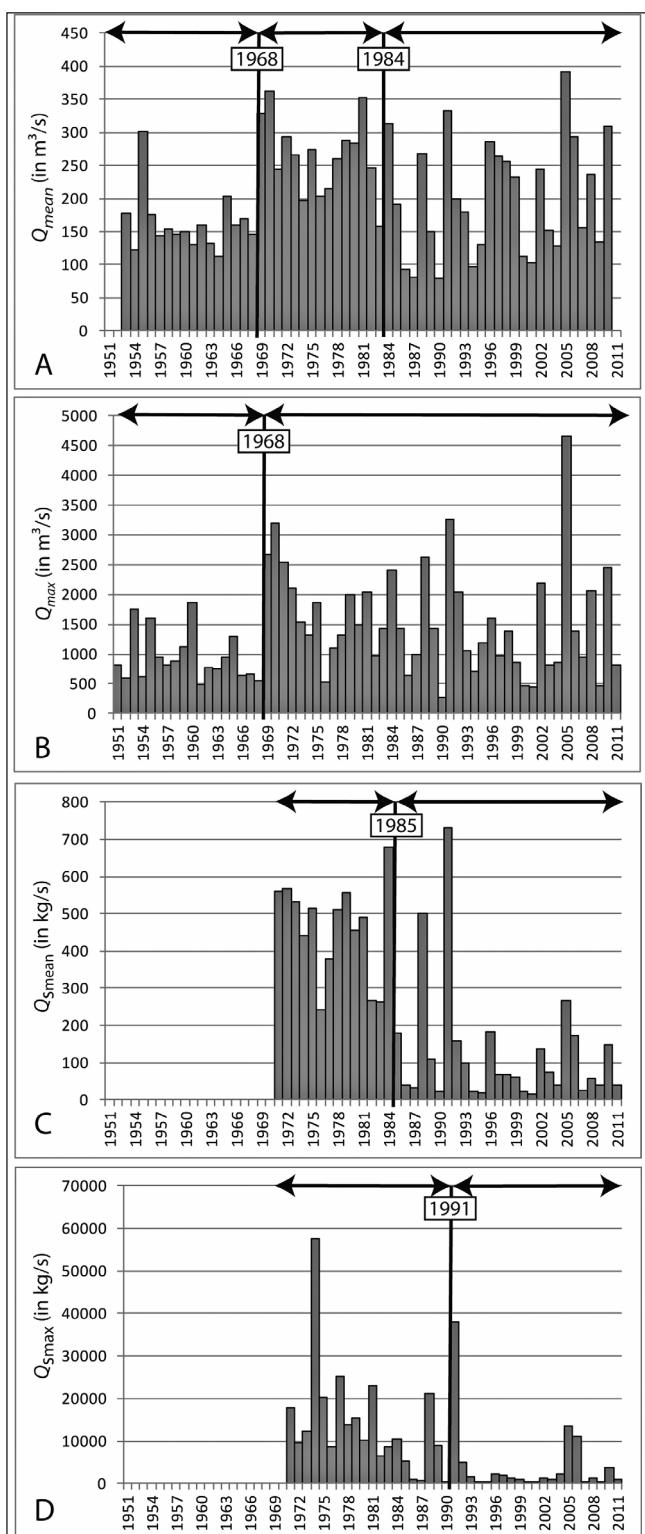


Fig. 4 – Water and sediment fluxes of the Siret River at the Lungoci hydrometric station. Mean annual discharge (Q_{mean}) from 1953 to 2010 (A); Maximum annual discharge (Q_{max}) from 1951 to 2011 (B); Mean annual suspended-sediment discharge ($Q_{s mean}$) from 1971 to 2011 (C); Maximum annual suspended-sediment discharge ($Q_{s max}$) from 1971 to 2011 (D). Data: ANAR-Siret Water Branch, GRDC.

Fig. 4 – Variation des débits liquides et d'alluvions en suspension à la station de Lungoci sur le Siret inférieur. Débits liquides moyens annuels (Q_{mean}) de 1953 à 2010 (A) ; Débits liquides maximaux annuels (Q_{max}) de 1951 à 2011 (B) ; Débits moyens annuels d'alluvions en suspension ($Q_{s mean}$) de 1971 à 2011 (C) ; Débits maximaux annuels d'alluvions en suspension ($Q_{s max}$) de 1971 à 2011 (D). Données : ANAR-Organisme du Siret, GRDC.

rainfall but an alternation of dry and wet years, and (ii) the period 1969-1972 was wet dominated. Ștefănescu et al. (2013) have studied the frequency of heavy (more than 50 mm) and extreme (+ 100 mm) rainfall in 24 h from 1980 and 2010 in 230 meteorological stations of Romania. They demonstrated that heavy and extreme rainfalls are more frequent and intense since 2000. In the present paper, six meteorological stations derived from data produced by the National Administration of Meteorology (ANM) were analysed at the Siret catchment scale in order to define a trend or cycles in the annual precipitation (tab. 3A). The Mann-Kendall test does not support the existence of significant change over time ($p < 0.01$) for annual precipitation. The probability to reject the null hypothesis when it is true is high (45%), thus there is no trend in the time series. The p -value of Pettitt test is too high to consider significant the various break points. Deviations from average were calculated in order to determine cycles in time series. A positive “anomaly” appeared for the whole six stations for the period 1969-1972. The variability of annual precipitation increased from 1980. Wet years (1984, 1991, and 2005) alternated with dry years (1986, 1990, 2000 and 2007) with no tendency evidence. The low discharge noticed in the 1950-1960s as well as the increase of the discharge in the 1970s can be explained by the precipitation variation. However, morphological changes, and particularly the active-channel narrowing, observed after 1970 cannot be explained by a climatic factor because these years are a relatively high-discharge period (fig. 4).

5.2. Role of land-cover use

Land-use changes may induce high hydromorphological responses in catchments. Land-use changes led to a decrease (soils covered by forest) or an increase (soils not covered by vegetation) of water and sediment discharges (Leopold et al., 1964; Boix-Fayos et al., 2007). A decrease of riparian forest may have increased both runoff and sediment supply whereas an extension of the riparian forest and its stability in time can have induced the narrowing of the active channel (Kondolf et al., 2002). According to Giurescu (1976), in 1976, the forest covered just one third of what it was in the early 20th century in the country. This intense deforestation was accused of provoking major floods in the 1970s, that's why the government conducted a strong afforestation policy

surrounding region. In their studies in Romanian Plain, Stefan et al. (2004) have demonstrated that there was no trend in annual precipitation during the period 1931-1999. Some periods (1943-1952; 1958-1968; 1980-1999) were marked by a meteorological and hydrological drought. Zaharia and Beltrando (2009) analysed the data of 20 meteorological stations for the period 1962-2006 for the Carpathian Arc region. They demonstrated by statistical analysis that (i) there was no significant trend (at monthly and annual timescale) in the variability of the

(Zaharia, 1998) after 1970, even if this policy began to a lesser extent in the 1930s. We do not have the exact data for the entire Siret River catchment but we can assess, thanks to topographical maps (1891, 1940 and 1981) and Corine Land cover data (2006), the evolution of the forest cover on the Lower Siret River between 1940 and 2006, and especially on the first reach (TR1) between 1891 and 2006. The forest cover in the first reach is not representative of the cover in whole catchment, but the variations from the beginning of the century are similar in the Siret catchment. From 1940 to 1981, the forest cover doubled (+ 70 km²) in the Lower Siret floodplain. Table 3B shows the evolution of the forest evolution more particularly on the first reach (TR1). The forest cover doubled from 1940 to 1970 and increased (+ 78.2%) from 1971 to 1981 due to flood protection policy. This extension is most of the time an extent of the riparian forest made of poplars. Two hypotheses can be made: (i) land-use change in the 1970s explains the narrowing of the active channel and the simplification of channel pattern by fixing banks and avoiding divagation; (ii) afforestation policy is part of a more extensive program of channel and flow regulation. The forest expansion was synchronous with the active-channel narrowing. The second hypothesis seems to be the more accurate because of two reasons. First the channel geometry cannot adjust its morphology so quickly. Second, thanks to technical engineering reports of 1970's we understand that afforestation policy was generally used to reduce the extension and the divagations of the riverbed.

5.3. Decisive impact of human intervention and arrangement

Seven dams located in the Siret River were built between 1977 and 2007, and the last two (Călimănești and Movileni) date from 1992 and 2007. The decrease in suspended-sediment discharge series cannot be explained by the dam's completion, which cannot be the first factor of the active-channel narrowing in the 1970s. First, narrowing phenomenon began earlier than dam's construction. Nevertheless, dams have accentuated the decrease of suspended-sediment after the year 1991. Second, both the rivers Putna and Buzău are tributaries that brought the highest values of suspended-sediment discharge in the Siret River (Rădoane and Rădoane, 2005), and they are located downstream of all the dams. Consequent-

ly, the dams can just explain the break point in suspended-sediment discharge between 1984 and 1991.

The dyke system appears as one of the most important factors impacting river morphology but it is variable, depending on reaches. The TR3 was channelised before 1940, thus there is no data to define a change due to engineering works. We assume that this early channelisation intended to protect the only foot bridge from the entire Lower Siret River upstream the confluence. After the major flood of 1970 and the highest annual maximum water discharges recorded from 1969 to 1975, the Romanian government decided to implement a strong flood protection strategy by building earth levees. That's why from the 70s (most probably after 1974 – SGA Vrancea, 1974), the river was channelised in TR2

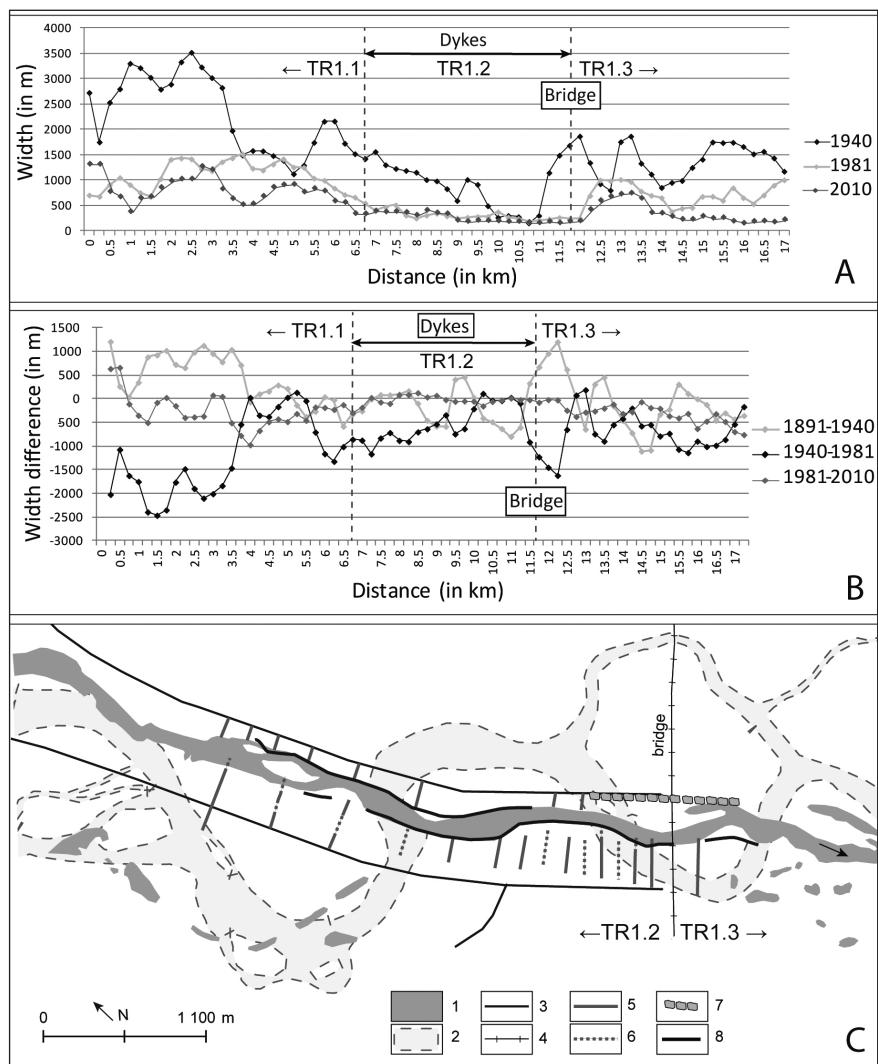


Fig. 5 – Evolution of the active channel width in the TR1 reach of the Lower Siret River from 1940 to 2010 (A) and comparison of the active-channel morphological evolution from 1891 to 2010 (B). The complex arrangements of sub-reach TR1.2 upstream of the Siret bridge (C). 1: Siret active channel 1981; 2: Siret active channel 1940; 3: dyke 1981; 4: railway; 5: groynes; 6: buried groynes; 7: embankments; 8: concrete pylons and slabs.

Fig. 5 – Évolution de la largeur de la bande active du Siret inférieur sur le TR1 de 1940 à 2010 (A) et comparaison de l'évolution morphologique de la bande active de 1891 à 2010 (B). Aménagement complexe du sous-tronçon TR1.2 en amont du pont du Siret (C). 1 : bande active du Siret en 1981 ; 2 : bande active du Siret en 1940 ; 3 : digue ; 4 : voie ferrée ; 5 : épis ; 6 : épis enterrés ; 7 : enrochement ; 8 : pylônes et plaques de béton armé.

and TR4 in order to protect lands and villages from floods. These dykes appear to be one of the first control factors of the limitation of channel migration. The first reach (TR1) is the most affected by narrowing and simplification of channel pattern. Active-channel narrowing began before 1981 especially in two sectors (fig. 5A): (i) between 0-5 km, a possible avulsion and the abandonment of a right-bank branch caused a strong narrowing; (ii) the implementation of a dyke system upstream of the Siret Bridge constrained the channel. The active channel was stable and narrowed from 1981 upstream of the bridge (TR1.2) whereas a channel widening appears upstream and downstream this area (TR1.1 and TR1.3; fig. 5B).

The second subreach (TR1.2) had known an extremely rapid channel contraction between 1970 and 1981 due to the building of engineering structures network (fig. 5C): twenty-two groynes buried or not and 4 km of rip-rap and concrete pylons were erected. These structures aim to avoid lateral erosion and channel widening in order to protect the bridge and arable lands near the villages. The groynes were made of 2x2 m concrete blocks perpendicular to the channel axis. Some of them were deeply destroyed and fell into the river due to lateral, bank erosion (fig. 6A). The single-thread channel shows evidence of erosion and widening, especially since 2005: in TR1 between 2005 and 2010, the mean width of the active-channel recorded an increase of 11% and a mean lateral erosion of 59 m (with a maximal value of 409 m recorded in TR1.1; Salit, 2013). This trend seems to be confirmed thanks to the field surveys between 2009 and 2012. The right-bank erosion was evaluated up to the number of fallen blocks (fig. 6A). Downstream from the Siret bridge (TR1.3), the lateral erosion reached 2 m/a. During this period, the 2010 flood event and the increase of in-stream-mining (fig. 6B) may have accentuated both lateral erosion and widening. In sum two phenomena occurred on the first reach (TR1) from 1970 to nowadays due to human interventions: (i) from 1970 to 1981 the active channel width narrowed due to regulation and channelisation; (ii) since 2005 the active-channel width recorded a widening due to the combine effects of floods, dam and in-stream mining.

On the Lower Siret River, human interventions such as dykes, dam and in-stream mining deeply modified the morphological pattern of the river. Climatic conditions and the associated hydrological events may have accentuated the morphological trend imposed by the overriding influence of the river engineering practices.

6. Discussion and conclusions

The results from this analysis of morphologic changes in the Siret River over time show an overall narrowing and



Fig. 6 – Evaluation of the lateral erosion in the Lower River Siret by quantification of destroyed groynes. (A) Note the seven fallen blocks (14 m) pointed by *. (B) In-stream mining in the active channel of the Lower Siret River. Photograph: F. Salit, October 2011.

Fig. 6 – Évaluation de l'érosion latérale sur le Siret inférieur par le dénombrement des épis détruits. (A) Les sept blocs tombés (14 m) sont indiqués par *. (B) Extraction de graviers en lit mineur sur le Siret inférieur. Photographies : F. Salit, octobre 2011.

simplification of channel form, but the trend of variations is different between reaches (fig. 7A). The first two reaches and especially TR1 show the major evolution (braided channel to single thread; narrowing) from 1970 to 1981, whereas the morphological dynamics of TR3 and TR4 are less pronounced. Several factors could explain these differences. First the initial patterns of reaches were different (braided for the first two; meandering for the last two) and a braided river is more sensitive at short and medium term to a change of water and sediment discharges (Schumm, 1977; Sambrook Smith et al., 2006). Then the engineering works appears earlier in the TR3 that limits dynamics of the riverbed. The combined actions of various engineering works in the 1970s associated with afforestation policy and dam completion after 1990s could explain the evolution of the TR1 and TR2. The input of suspended load by main tributaries in TR3 and TR4 could explain the less morphological changes/dynamics of the two last reaches, but engineering works lead to a stabilisation of all parameters.

K.J. Gregory (2006) pointed out five questions dealing with the human role in changing river channels: what, how, when, where, and why. This paper answers some of these

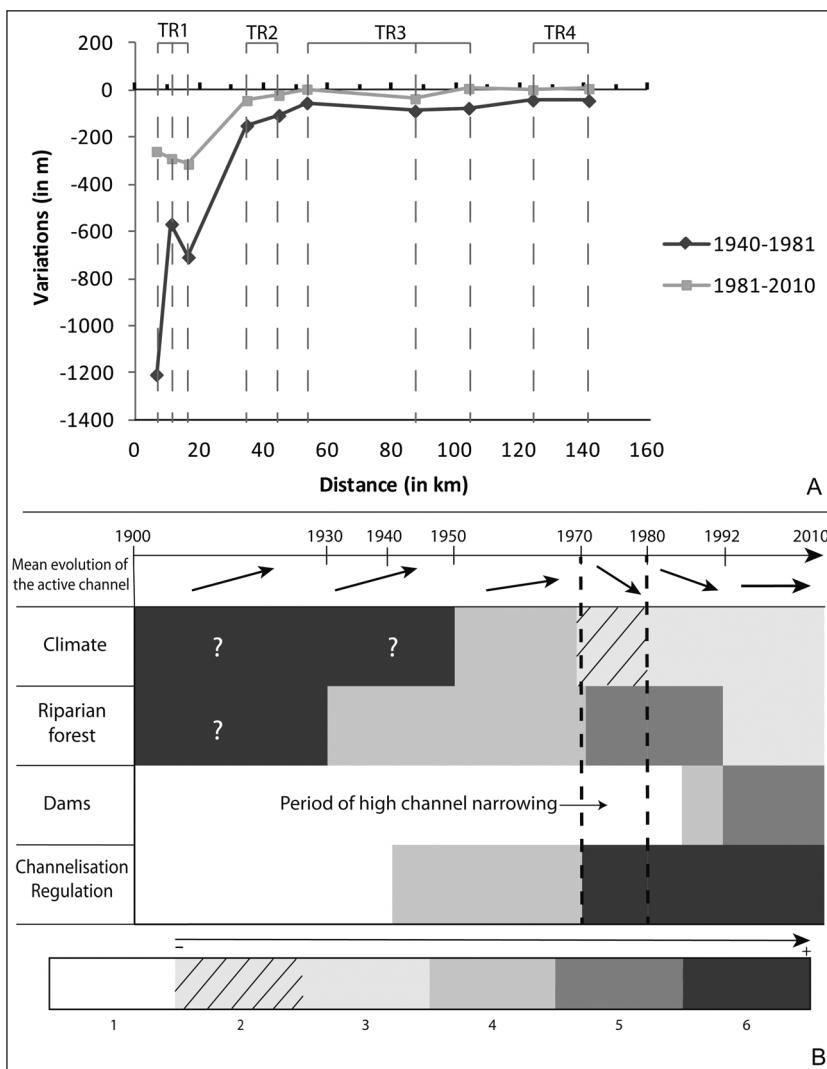


Fig. 7 – The compared trend of the active channel width on the different reaches of the Lower Siret River from 1940 to 2010. A: Relative weight of the factors controlling the geomorphological evolution of the Siret active channel from the beginning of the 20th century to 2010. B: Upward arrow; increasing mean channel width; downward: decreasing mean channel width. 1: no data; 2: no weight or opposed factor; 3: no weight; 4: aggravating factor; 5: important factor; 6: major factor.

Fig. 7 – Évolution comparée de l'évolution de la largeur de la bande active sur l'ensemble des tronçons du Siret inférieur de 1940 à 2010. A : Poids relatif de chacun des facteurs contrôlant l'évolution morphologique de la bande active du Siret inférieur du début du XX^e siècle à 2010. B : Flèche montante ; augmentation de la largeur moyenne de la bande active ; Flèche descendante : diminution de la largeur moyenne de la bande active . 1 : pas de données ; 2 : pas de poids voire même facteur contraire ; 3 : pas de poids ; 4 : facteur aggravant ; 5 : facteur important ; 6 : facteur majeur.

questions: in the Lower Siret River, morphological adjustments, especially active-channel narrowing, can be first of all explained by engineering interventions rather than just climatic variability, particularly in the 1970s. Engineering works were built in order to control the river dynamics and location and to protect lands and population from “*the harmful effects of the water*” (Hâncu, 1976). But there is no single answer to the spatial and temporal variations of the morphological channel adjustments in the Lower Siret River. The weight of each factor, climatic and human, in the active-channel dynamics is synthesised in fig. 7B. Five phases of change can be distinguished:

(i) 1900-1950: The lack of climatic data before the 1960s in the Siret catchment permits only speculation. The engineering works really appear in 1940 but ramped up after 1970. Thus, only climatic drivers and land-use changes could lead to the widening of the bed during the first part of the century such as we noticed on the TR1.1. Thus, climatic conditions and deforestation could lead to active-channel widening by an increase of water and suspended-sediment discharges. From 1930, the beginning of afforestation policy could lead to reduce the weight of land use cover in the dynamics of active-channel width.

(ii) 1950-1969: active-channel width increased less quickly due to various factors (decrease of precipitation, afforestation) and it is difficult to determine the most important one.

(iii) 1970-1983: channel engineering combined with afforestation led to active-channel narrowing. The climatic factor (increase of precipitation) cannot explain this trend since higher discharges from increase rainfall should lead to an increase of channel capacity. The management strategy following the 1970 flood led toward a narrower, single-thread, less complex channel structure.

(iv) 1984-1991: dams and channelisation contributed to the active-channel narrowing.

(v) 1992-2010: channelisation led to the planform stability of the active channel, which can only adjust its morphology by incision. The in-stream mining developed since 2005 seems to exacerbate channel incision even if no data are available for the moment (fig. 6B). The 2005 «reference» flood event changed the positive vision of the river engineering strategy, especially in the Lower Siret River (Salit et al., 2013). The future engineering works (such as groynes) strive to protect the riverbanks from lateral erosion causing by all previous engineering works.

This lateral erosion threatens villages and since 2009, seven new projects of banks protection were planned. However it seems that this dynamics lead to justify in-stream mining. Intense in-stream mining is motivated at a regional scale in in-stream mining environmental impact assessment (EIA) by several explanations: it aims avoiding lateral erosion and dredging river channel in order to increase its capacity and then prevent floods (Salit and Ioana-Toroimac, 2013). This strategy appears in contradiction with European directives and further investigations should be conducted to assess the morphological effects of in-stream mining in this area. The Lower Siret River experienced severe changes since the 1970s due to combined human factors. During this

period, climatic variability and the associated hydrological events can be considered as triggering factors, which caused the activation of a systematic and complete water management strategy. In the Lower Siret catchment, management strategy plays a key role in the dynamics of the fluvial system more than any other variable. The major flood of 2005 involved a similar political will with beneficial effects that it will be possible to evaluate in the coming years.

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