Anthropogenic activities since the end of the Little Ice Age: a critical factor driving fluvial changes on the Isonzo River (Italy, Slovenia)

Activités anthropiques depuis la fin du petit âge glaciaire : un facteur critique contrôlant la métamorphose fluviale de l'Isonzo (Italie, Slovénie)

Isabelle SICHÉ
University of Paris-Diderot (Paris 7)
CNRS (UMR 8586 PRODIG)
Paris, France

Gilles ARNAUD-FASSETTA
University of Paris-Diderot (Paris 7)
CNRS (UMR 8586 PRODIG)
Paris, France
gilles.arnaud-fassetta@univ-paris-diderot.fr

Abstract: *The Isonzo is a 140-km long river that draws its source in the Julian Alps in Slovenia and joins the Gulf of Trieste in the Northern Adriatic, Italy. Its catchment area (~3400 km²) consists of mid-altitude mountains (70%), a piedmont (22%), and a coastal plain (8%) influenced by Mediterranean climatic conditions. The river is a high-energy system due to its pronounced hydraulical gradients and with frequent damage to man-made structures. The objective of this study is to determine the recent functioning of the Isonzo River by (i) a diachronic (from the Little Ice Age), plan-form analysis of the alluvial plain, using old maps, topographic maps of the IGM and aerial photographs, and (ii) an analysis of channel incision and sediment transport, using data derived from national and regional water services and field observations. Over the last 200 years, the Isonzo River shows a clear tendency to active-channel narrowing between 15 km and 2 km upstream of the river-mouth. This phenomenon was accompanied by an incision of the active channel, estimated to be between 0.5 m and 1.5 m at the most vulnerable sites. In the context of climate change since ca. 1860, the narrowing/incision of the active channel increased from the 1880s to 1920s, and prticularly since 1960, because of human impacts (channelisation, embankments, dams) in the catchment, and despite the increase of flood frequencies. The recent hydro-morpho-sedimentary functioning of the Isonzo shows that the river is still in a transitional phase towards a physical equilibrium that changes after every human intervention in the active channel.*

Key words: Isonzo River, Italy, Little Ice Age, post-Little Ice Age, fluvial metamorphosis, anthropogenic impacts

Résumé : L'Isonzo est un fleuve long de 140 km qui prend sa source dans les Alpes Juliennes en Slovénie et se jette dans le golfe de Trieste en Italie, au Nord de l'Adriatique. Son bassin-versant (~ 3 400 km²) est constitué de moyennes montagnes (70 %), d'un piedmont (22 %) et d'une plaine côtière (8 %) sous conditions climatiques méditerranéennes. Le fleuve dispose d'une forte énergie en raison de gradients hydrauliques élevés, à l'origine de dommages causés chaque année aux ouvrages d'art et aux structures hydrauliques. Cette étude a pour objectif de déterminer le fonctionnement actuel de l'Isonzo par 1) une approche diachronique de l'état de surface dans la plaine alluviale depuis le PAG, utilisant pour cela des cartes anciennes, des cartes topographiques de l'IGM et des photographies aériennes, et 2) l'analyse de l'incision du chenal couplée au transport sédimentaire, grâce aux données des services hydrauliques nationaux et régionaux et des observations de terrain. Depuis 200 ans, l'Isonzo montre une nette tendance à la contraction de sa bande active sur le tronçon situé entre 15 km et 2 km en amont de l'embouchure. Ce phénomène s'est accompagné d'une incision du chenal, estimée entre 0,5 m et 1,5 m dans les secteurs les plus touchés. Amorcé à la faveur d'une amélioration climatique depuis 1860, la contraction/incision du chenal s'est accélérée à partir des années 1880 puis des années 1920 et, surtout, depuis 1960, à cause des actions anthropiques (chenalisation, endiguement, barrages-réservoirs) dans le bassin-versant et ce, malgré l'augmentation de la fréquence des crues. Le bilan hydro-morpho-sédimentaire montre que le fleuve est encore dans un stade de transition vers un équilibre physique qui se modifie à chaque intervention humaine dans le chenal d'écoulement.

Mots clés : Isonzo, Italie, petit âge glaciaire, post-petit âge glaciaire, métamorphose fluviale, actions anthropiques

The Isonzo River (Soča in Slovenia), a cross-border river straddling the Italo-Slovenian border, constituted a combat front during the two world wars (fig. 1A). The river is 140-km in length and drains a small catchment (~3400 km²) located in the Julian Alps. Downstream of the mountainous area, the Isonzo River flows through the piedmont and coastal plain, including the region of Friuli-Venezia Giulia, and the wave-dominated delta (COVELLI *et al.*, 2004) prograding in the Gulf of Trieste, in the north of the Adriatic Sea. The main interest of the Isonzo River is the precocity of structures built on the flood plain, beginning with the Austrians in 1880. These human interventions profoundly changed the hydro-morphological functioning and could have accelerated the metamorphosis of the active-channel geometry from the end of the Little Ice Age (LIA), according to the typology of recent river changes proposed by ARNAUD-FASSETTA and FORT (2014). In spite of the dispersion of data sources in three countries (Austria, Italy and Slovenia), the aim of this paper is to better understand the respective role of the hydro-sedimentary and human factors that controlled to the last 'fluvial metamorphosis' (*sensu* SCHUMM, 1977) of the Isonzo River. The fluvial changes are discussed in the last two centuries in order to take into account the effects of the LIA and climate change during the 20th-21st centuries. Derived from the hydro-geomorphological mapping of the Isonzo River over the last 26 km before its outlet in the Adriatic Sea, the evolution of its active channel is analysed from the adjustment variables (channel width, channel incision, braiding index, sinuosity index). This study demonstrates the rapid channel changes of the Isonzo River at the centennial scale, and identifies the key factors controlling its metamorphosis, mainly of anthropogenic origin.

1 - Study area

1.1 - Morpho-structural units, hydrography, and alluvium discontinuum

The Isonzo is a 140-km long river that rises in the Julian Alps in Slovenia and joins the Gulf of Trieste, Northern Adriatic, in Italy (fig. 1A). With an area of 3416 km² (MOSETTI, 1986), the Isonzo catchment, the largest in the Friulan-Slovenian region, is divided into three physiographic units (PU): the mountain (70%), its piedmont (22%) to the line of karst resurgences, and the coastal plain (8%).

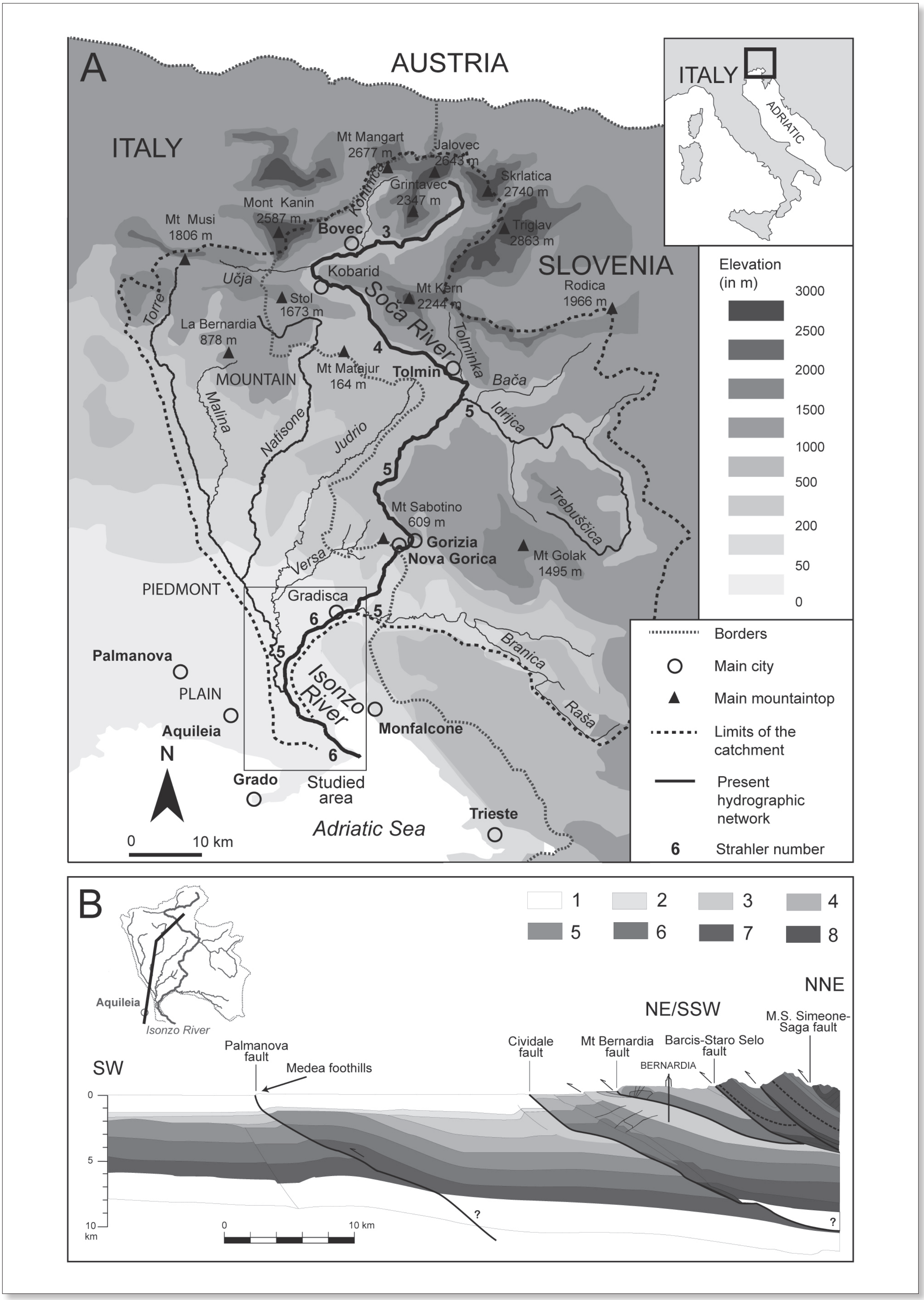

Fig. 1 – Physiography, hydrography and geology of the study area. (A) The Isonzo catchment. (B) Geological section across the mountains, the piedmont and the coastal plain in the Isonzo catchment (after Merlini *et al.*, 2001). 1: Quaternary formations; 2: Canavella Formation; 3: Flysch of "Grivo"; 4: Flysch of Cormons; 5: Cretaceous limestone; 6: Jurassic limestone; 7: Dolomites; 8: Montebello Formation.

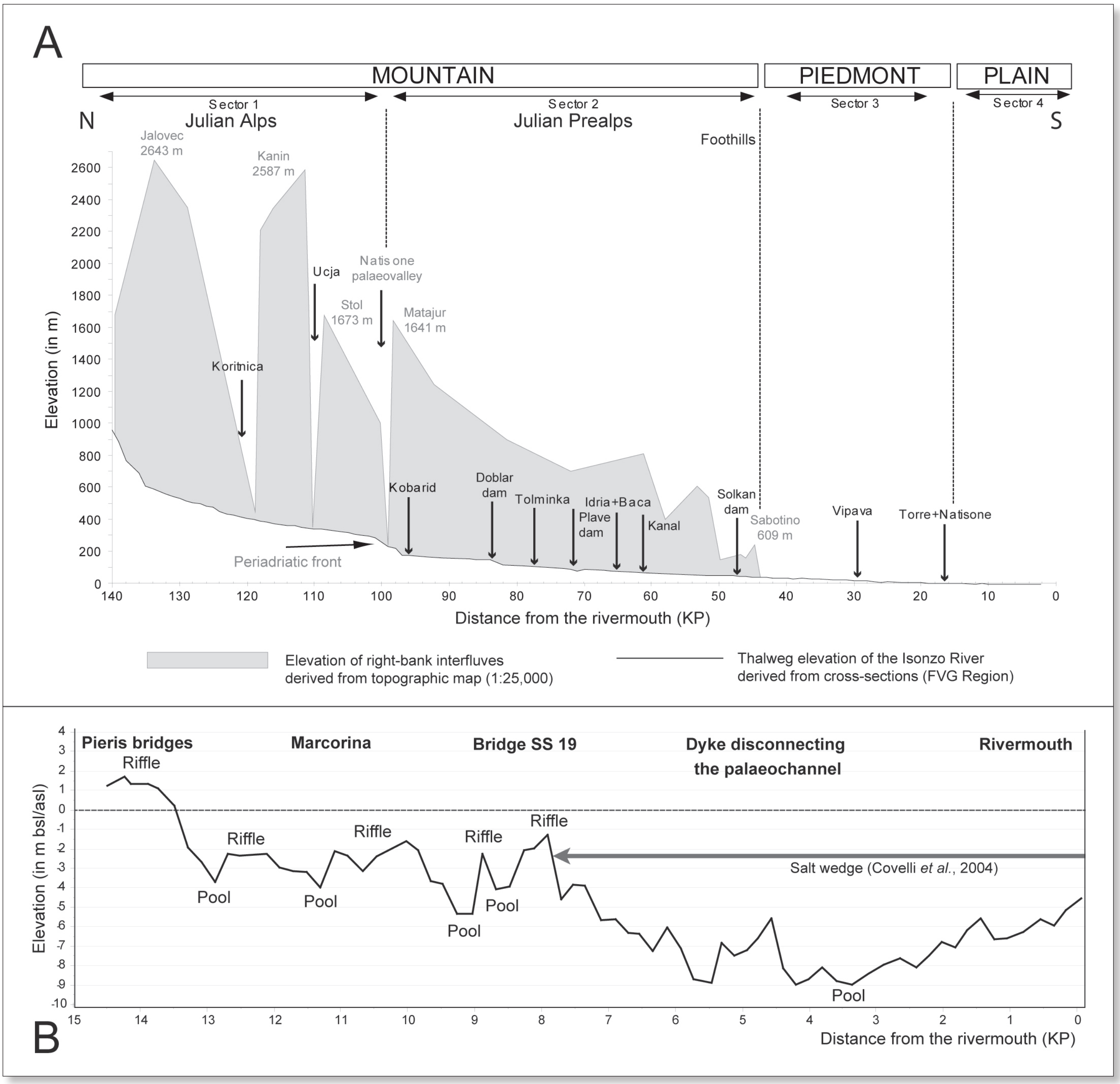

Fig. 2 – Longitudinal profile of the Isonzo River. (A) General longitudinal profile. (B) Detailed view of the longitudinal profile from the KP 15 to the river mouth, derived from the altitude of the thalweg measured on the 1979 cross-sections.

The mountainous PU, of low to moderate altitude [mean elevation: 1030 m; highest point (Triglav): 2860 m] is the interface between two Alpine structural units: (i) the Torre and Natisone basins falling within the Julian Prealps (Southern Alps) and (ii) the Isonzo basin in Slovenia which is part of the Julian Alps (Dinaric domain; fig. 1B). The hydrographic network is essentially mediated by the structural framework (*i.e.*, faults of the Alpine or Dinaric ranges). The values of specific stream power are very high (up to 1900 W/m^2 between Idria and Doblar; SICHÉ, 2002) because of steep slopes (fig. 2A) up to Gorizia, where the Isonzo River enters in the piedmont.

The piedmont of PU is formed by the coalescence of megacones built by the torrential rivers of the Isonzo, Torre, Natisone, and Judrio-Versa (MOZZI, 1995; FONTANA, 2002; BONDESAN and MENEGHEL, 2004). The Isonzo and Torre megacones have concave longitudinal profiles, whose slope reaches 8‰ at the apex (fig. 2B), leading to an important transport and storage of bed-load deposits (gravel and pebbles with sandy matrix with openwork texture). Apart from the incision of streambeds, the relief is very low (several metres). The large size of megacones gives the rivers the possibility to adopt several, successive channel patterns in a general context of high energy (specific stream power ~300-100 W/m^2; SICHÉ, 2002; fig. 3A). These megacones are fossilised in the distal, Pleistocene part by Holocene deltaic deposits (Marocco, 1991 a and b; Siché, 2008) forming the coastal plain.

With a maximum elevation of +4 m asl, the coastal-plain of PU is characterised by gentle slopes (<5‰), leading to a drop in river competence, transport capacity and deposition of bed-load material (sand and silt). The specific stream power of the Isonzo River varies from 35 to 3 W/m^2 (SICHÉ, 2002). The decrease in the energy gradient controls the downstream fining of grain-size (fig. 4). Around 3 km from the seashore, the coastal plain, with a slope of just 0.5 ‰, is formed by the coalescence of the Isonzo wave-dominated delta (fig. 3B), the deltaic lobe of the Isonzato, abandoned and regularised, and the lagoons of Grado and Marano.

Fig. 3 – The succession of channel patterns of the Isonzo River on the last 15 km of its course before the river mouth in the Adriatic Sea (aerial photo: Luigi Cargnel, 1991). (A) At KP 15, under the Pieris road and rail bridges, the river is sinuous and its bed is gravely. The lateral bars are regularly re-colonised by pioneer vegetation. The "*Golena*" is left almost entirely to the riparian vegetation. In the foreground, an ancient gravel pit. (B) At KP 6, the river is sub-straight with a silty load (aerial photograph: Regional Nature Park "Foce dell' Isonzo"). In the foreground stands the dyke separating the Quarrantia palaeochannel and the present Isonzo channel. The outer flank of the levees, whose slope is discernible, is covered by trees.

In summary, the Isonzo River maintains its braided channels up to 20 km upstream from the river mouth. The transition to a sinuous, single channel occurs over a very short distance downstream of the last 15 km at the piedmont/coastal plain interface (ARNAUD-FASSETTA *et al*., 1999), where the energy slope breaks off. The longitudinal profile controls the decrease of the specific stream power and the competence of the river. Sediment transport is mainly dominated by rolling and saltation processes in the piedmont, and saltation and graded suspension over the last 10 km (BRESSON, 2001).

1.2 - Climate and hydrological functioning

Located on the northern margin of the Mediterranean area, the Isonzo catchment is part of a zone traditionally included in the temperate oceanic domain with Mediterranean influences (GENTILLI, 1964; VIGNEAU, 2001). The rainfall follows a NE-SW gradient (1000 mm/a in Aquileia; 1500 mm/a in Gradisca; more than 3200 mm/a on the eastern flank of the Triglav and in the Učja valley), related to orography (CEGNAR, 1998; FREY and SCHÄR, 1998). Rainfall regimes, with a dry season in February and July and two precipitation maxima in fall and spring, determine the hydrological regime of the Isonzo River.

The hydrological regime of the Isonzo River is torrential, characterized by inter- and intra-annual variability (CUCCHI, 2003; COMICI and BUSSANI, 2007). At the Solkan station, the mean discharge of the Isonzo River is 95.5 m^3/s, while the minimum and maximum discharges over 30 years (1961-1990) are 31 m^3/s and 2253 m^3/s, respectively. The bankfull discharge ($Q_{1.5}$), the 5-year recurrence interval (RI) flood (Q_5) and the 20-year RI flood (Q_{20}) are 1050 m^3/s, 1663 m^3/s and 2035 m^3/s, respectively (SICHÉ, 2008). Floods of the Isonzo River and its main tributaries (Torre, Natisone) are distinguished by the rapid progression of the flood waves (*i.e*., flash floods). The 100-year RI flood (Q_{100}) of the Isonzo River occurred in 1940. Exceptional floods remain poorly understood because the records of the Wasserkraft Kataster hydrogrammes do not begin until 1877 (Isonzo) and 1896 (Torre), when the rivers were almost corseted by dykes. We know that the Isonzo River burst its dykes in 1940 and 1979 but the inundation of the flood plain was limited to the areas of Turriaco and Isola Morosini (COMEL *et al*., 1982).

1.3 - Land use and recent river management

Austro-Hungarian domination, from 1420 to 1918, did not bring significant changes in the location of urban sites built since antiquity (ARNAUD-FASSETTA, 2003; SICHÉ *et al*., 2006) and structures settled along the Isonzo valley. However, from the second half of the 20th century, energy requirements needs and the will to develop a productive agriculture system led to significant and irreversible changes in the morphology of riverbeds and sediment transport dynamics (SICHÉ, 2008; fig. 5).

1.3.1 - General considerations at the catchment scale

The recent evolution of the catchment led to a dichotomy between the mountain and its piedmont. In 1880, alluvial fans in Slovenia and around Gorizia were cultivated, including vineyards in the piedmont. However, the Slovenian Alps remained sparsely populated (30 inhabitants/km^2) during the 19th century. The decline of the traditional agro-forestry-pastoral system has promoted the establishment of reforestation policies at the expense of pastures. For instance, the forested areas increased from 40% in 1896 to 50% in 1994 (GABROVEC and KLADNIK, 1997).

In the early 2000s, the system evolved once again with a contrast between wooded mountain/cleared piedmont,

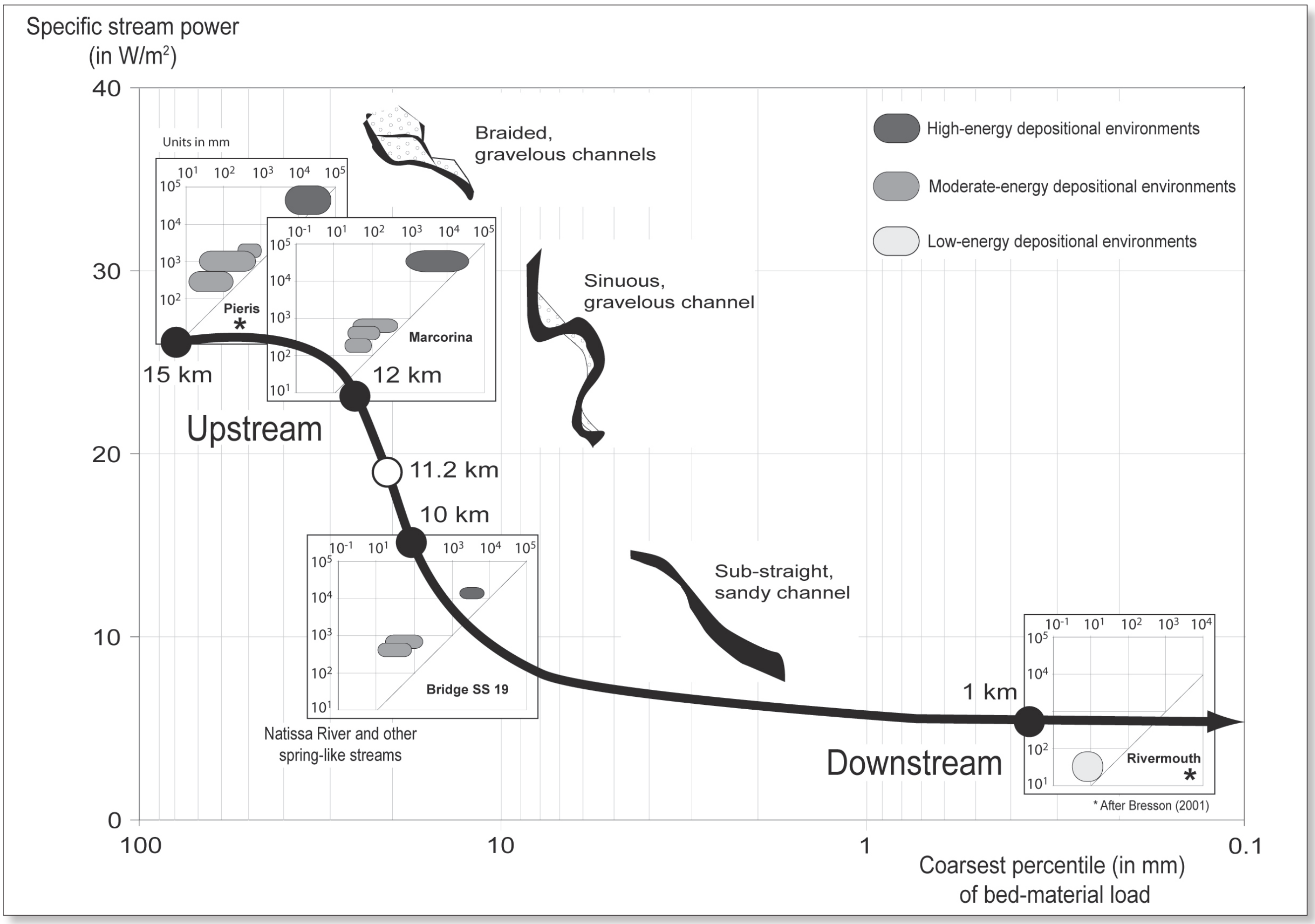

Fig. 4 – Downstream fining of the Lower Isonzo alluvium expressed as the CM pattern [Passega, 1957] *vs.* specific stream power [Bagnold, 1977], according to the sedimentological model proposed by Bravard and Peiry (1999).

with three types of development in the valleys: (i) Slovenian mountains being of moderate altitude, the forest reaches the ridgelines with the exception of the peaks exceeding 2000 m (*e.g.*, Triglav) in the Julian Alps. Therefore, the forests comprising *Acacia* and softwoods presently cover the slopes and invade the floodplain, leaving only a narrow active channel. The PUH (Podjetje za Urejanje Hurdunikov, which is the agency for river management) has contributed to this trend by applying a policy of slope reforestation and river management in order to mitigate against soil erosion, especially in the middle part of the catchment characterised by flysch formations. (ii) The valley bottoms, if large enough for human settlement, are occupied by meadows. (iii) The alluvial fans are used for pastural activities and are equipped with retaining walls (*e.g.*, Mt Kern) to limit the migration of debris on their margins.

The Isonzo valley in the piedmont has two configurations. Flysch hills of the Prealps and the residual reliefs of the apical part are terraced to provide support for the vineyards. In decline since the late 19th century, they have today been replaced by cereal crops in open fields on the rest of the piedmont, the coastal plain, and the alluvial terraces along with the distal part of the flood plain (also called "*Golene*").

1.3.2 - Water projects

Most European rivers, such as the nearby Tagliamento River, are equipped with hydropower installations or water extraction systems for irrigation. These structures affect energy levels and disturb the sediment transport in both the channel and the floodplain. During the past two centuries, the Isonzo channel has experienced three phases of water development:

- (i) Early Austro-Hungarian hydraulic structures: the *Jahrbuchs* (since 1895) and 1:75,000 topographic maps (1880) testify to the construction of milldams (Straccis, Gorizia, Gradisca, Sagrado) that have deflected part of the river discharge (*i.e.*, ~21 m^3/s) into artificial channels for industrial and agricultural uses. They meet the needs of a textile factory in Gorizia and are also used to irrigate crops in the upper piedmont. This is the case of the Dottori channel built from 1894 to 1905 (fig. 5). Finally, the river was dammed along much of its course, up to 10 km from the river mouth.

- (ii) The river and the economic policy of Mussolini's Italy: after the First World War, the whole catchment was included in the Italian territory. Following the takeover of Mussolini, hydroelectric facilities were built in the Isonzo catchment received in order to modernize the Nation and produce energy. The construction of two hydropower plants marks a major milestone in the history of the Isonzo River (fig. 5). The first one (He Doblar) was built in 1939 in the Most Na Soči canyon (dam: 45-m high; dam drop: 33 m; reservoir capacity: 6.5 million m^3; water intake: 90 m^3/s) to feed the underground powerplant near Doblar (power: 30 MW). The second one (Plave)

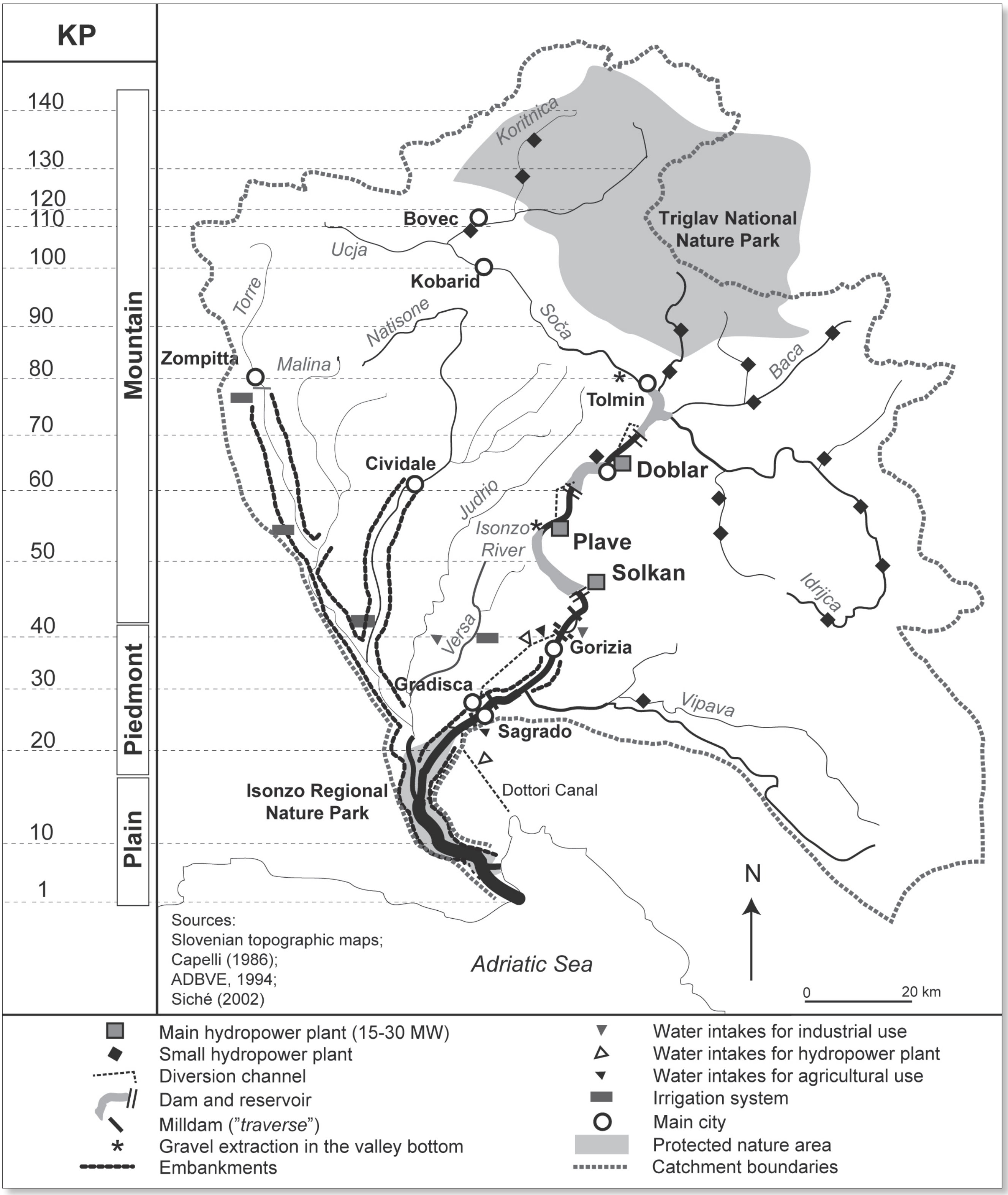

Fig. 5 – Human action and activities (hydraulics, sediment, conservation) in the Isonzo catchment.

was built in 1936 on the same principle (dam: 25.5-m high; reservoir capacity: 1.7 million m^3: water intake: 90 m^3/s; power: 15 MW). The Second World War put a stop to this hydroelectric development. The upper Isonzo catchment was assigned to Zone B of the Treaty of Paris in 1947 and became Yugoslavia in 1954. Zone A, which included the piedmont and the coastal plain, is Italian. The milldams were maintained and the water intakes were used for small hydropower plants. The water intake on the Gradisca milldam was used for a new textile factory. Finally, a new milldam was added upstream of Gorizia for the same reasons (fig. 10A).

- (iii) The hydraulic and sediment management of the Isonzo River and its tributaries for 60 years: Slovenia has continued to develop its hydroelectric potential with the Soške Electrarne. The Solkan dam

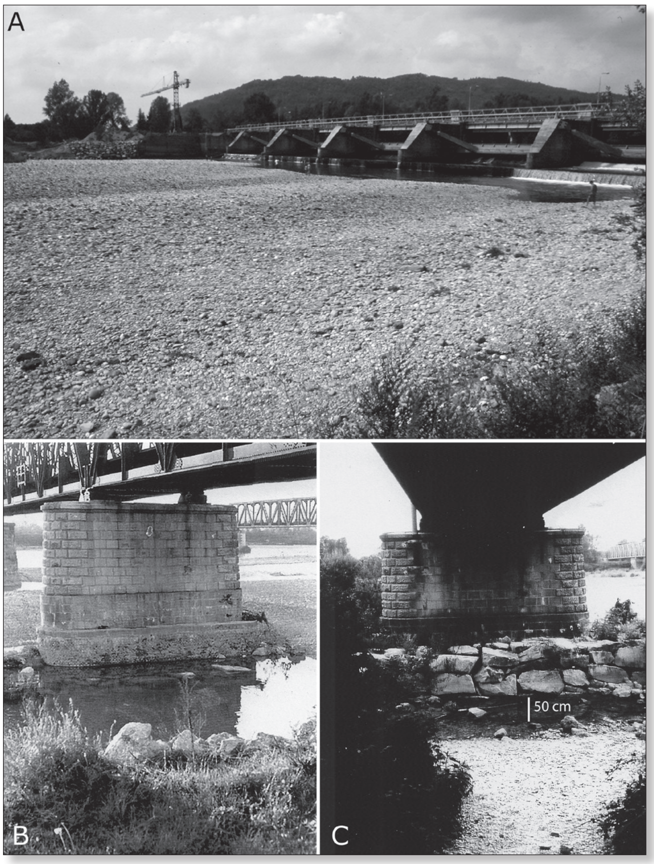

Fig. 10 – Sediment retention by dams and the impact of channel incision on the hydraulic structures along the Isonzo River. (A) The Gorizia dam on the Isonzo River. *Photo: G. Arnaud-Fassetta, August 1999*. The dam interrupts the downstream bed-load (gravel and pebble) transport. (B) The Pieris railway bridge on the Lower Isonzo River in 1979. *Photo: A. Canziani*. The bridge piers begin to be scoured but the phenomenon is of lower magnitude. (C) The Pieris railway bridge on the Lower Isonzo River in 2000. *Photo: I. Siché*. The bridge piers are now protected by riprap in order to limit the impact of severe channel incision estimated to >1 m (>3 cm/a).

(20-m high) was built in 1981 near the hydropower plant (reservoir capacity: 1.15 million m^3; water intake: 93 m^3/s; power: 33 MW). Between 1999 and 2002, the power output of Doblar and Plave plants was increased. The reservoirs' capacity was not modified but a second intake (105 m^3/s) was built on each of them to increase the discharge up to 190 m^3/s. Downstream, the Isonzo channel has a minimum discharge of only 2 m^3/s. In Italy, there was no significant change in this respect. Hydropower plants were built in existing Gradisca and Gorizia channels in 1960. The Quarantia channel was dug in 1954 to facilitate navigation in the river mouth. The second half of the 20th century was the period of greatest human disturbance of the bed load in the Isonzo channel. The building of a new dam along with gravel extraction in the flood plain (BRAMBATTI *et al.*, 1981). On the floodplain, major campaigns for land reclamation led to the disconnection of secondary channels, the expansion of flood plains, the draining of swamps and salt marshes of the Gulf of Panzano, and the reduction of the riparian forest along the riverbanks. This phenomenon was contemporaneous with the embankments of the Isonzo River up to its river mouth. Only the protected areas of Triglav National Nature Park (Slovenia) and Isonzo Regional Nature Park (Italy) are relatively 'natural'.

2 - Methods

2.1 - Selected area

The piedmont and the coastal plain drained by the Isonzo River extend between the kilometric points (KP) 40 and 1 (*i.e.*, between Gorizia and the river mouth). We chose to focus on this area, where a double transition occurs between the braided channels and the single, sinuous then sub-straight channel, *i.e.* downstream of Gradisca (KP 26). This transition between three channel patterns over a short distance is the specificity of the Isonzo River, compared with the other rivers of the Padan Plain. In this area of low slope (<8‰), braiding and meandering shift rapidly because the river can deposit or erode the bed load (SCHUMM, 1977). This area is also characterised by a strong lateral instability of the active channel, whose width can reach 1.5 km.

A

Type of document	Title	Scale	Date	Authors
Topographic maps	"Military reconnaissance of Friuli Region ordered by Marshal Massena"	1:50,000	Winter 1806	Engineers geographers
	Spezialkarte von Österreich-Ungarn Maps Flitsh/Bovec, Görz, Triest	1:75,000	1880	K.K. Militär geographisches Institut
	Carte topografiche F° 44A	1:25,000	1918 & 1926	Instituto geographico militare (IGM)
	Carte topografiche F° 44A	1:25,000	1938	Instituto geographico militare (IGM)
	Carte topografiche F° 44A	1:25,000	1962	Instituto geographico militare (IGM)
Aerial ortho-photographs	"Fiume Isonzo" Ordered by Gorizia Civil Engineering	1:25,000	May 1979	Aerofotogrametria (Garizzazi & cie)
	Missions for photogrammetry	1:25,000	1998	Regione Autonoma Friul Venezia Juliana

B

Nomenclature	Type of document – Place of conservation – Date of publication
P1	Aerial photographs – Trieste; Regione autonoma Friuli Venezia Gulia – 1935
P2	Aerial photographs – Trieste; Regione autonoma Friuli Venezia Gulia – 1954
P3	Ortho-photogrammetry – "Fiume Isonzo", Gorizia Civil Engineering – May 1979
P4	Aerial ortho-photographs – Trieste; Regione autonoma Friuli Venezia Gulia – 1998

Fig. 6 – Data collection and methods. (A) General methodology: from maps to zoning and quantification of the active-channel geomorphological changes. (B) List of iconographic data used for mapping. (C) Types of aerial photographs used in this study.

2.2 - Iconographic data

In this study, we primarily used aerial photographs (fig. 6 A and B). The reliability of the information depends largely on shooting conditions. The surveys of 1938, 1954 and 1979 were selected for their sharpness and high contrast. However, we discarded (i) the 1985 surveys because of their poor contrast and small scale, and (ii) the 1991 surveys because we had access to recent orthophotographs (1998). The 1998 surveys were carried out several months apart and it was difficult to identify if the alluvial bars were emerged or if the water was turbid in summer. The 1954 surveys are incomplete around Pieris. In addition, water-level variations create distortions in the calculation of the braiding index.

Topographic maps did not allow the same analysis as the precision of the outlines and the level of detail of the legends varied according to the publishers and the method of data collection (fig. 6A). (i) The Napoleonic map of Friuli was drawn-up in the winter (date? November-January), the usual period of low river flow. It mainly provides qualitative information (wet or vegetated land), but it is not possible to discern if the channels are under-represented or if gravel bars are simplified or not. (ii) The 1880 map presents the same drawbacks but to a lesser extent because of the accuracy of the surveys. The main quality of this edition is the fine line of natural areas (bushes, moors, meadows, areas occasionally submerged, permanent swamps, natural or anthropogenic reeds). (iii) Maps of the IGM, which are of good quality, were derived from the Austrian surveys of 1917. Their only weakness is the poorer detail with regards to the type and the extent of the vegetation.

These documents did not use the same projection system. Therefore we normalized all the cartographic sources using orthorectification with ArcGIS 9.1 from the 1:25,000 Regional Technical Map. The control points are major points of interest, such as crossroads or church steeples,

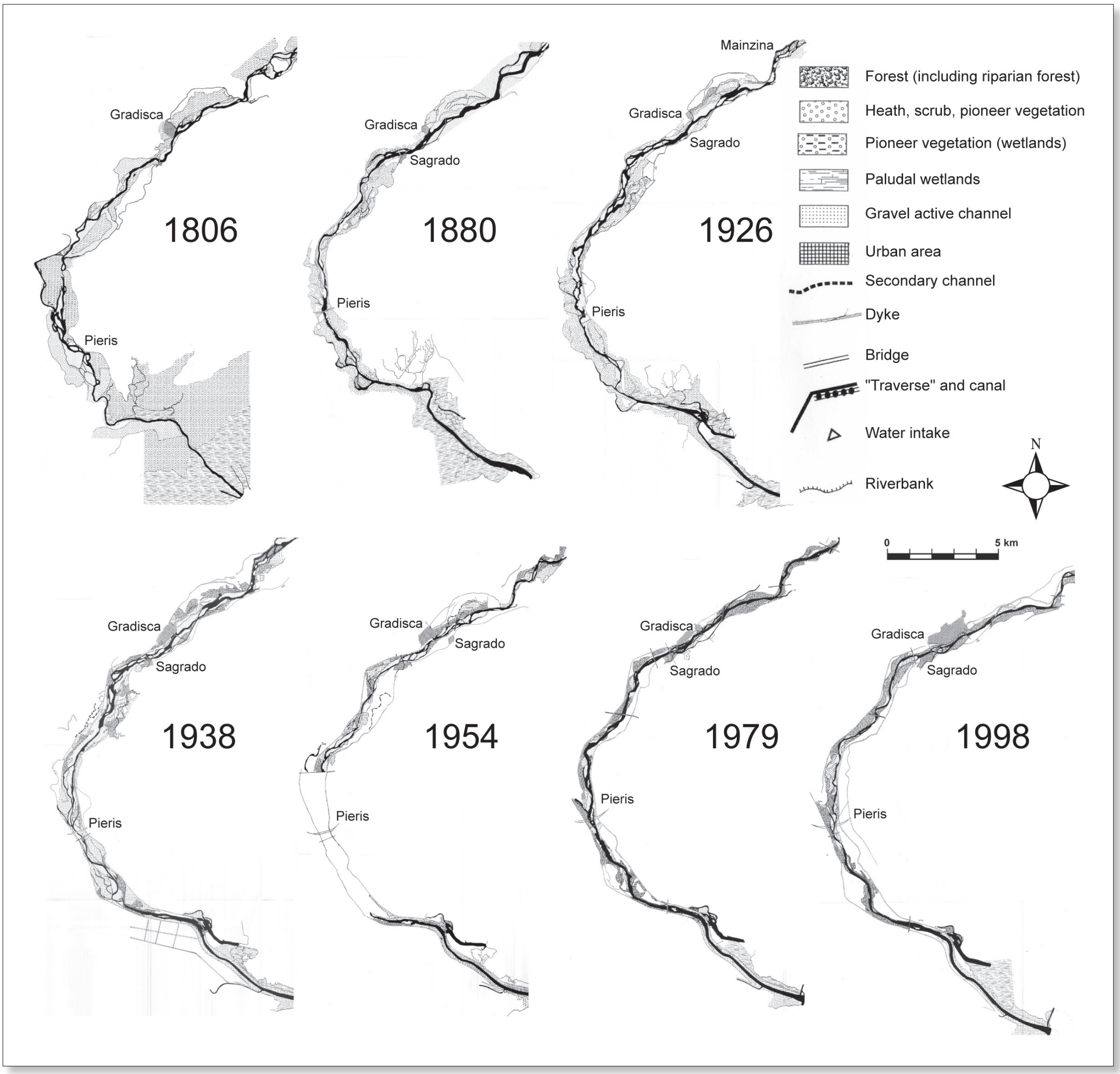

Fig. 7 – Diachronic mapping (1806-1998) of the Isonzo floodplain between Gradisca and the river mouth.

and are not likely to have changed. However, we must keep in mind two limitations to the quantitative analysis of this type of support: (i) The margin of error is the measurement of the thickness of the line. It varies depending on the scale [2.5 m on the maps of the 20th century (1:25,000); 7.5 m for the 1880 map (1:75,000); 14 m for the 1806 map (1:50,000)]. The error margin on aerial photographs depends on the resolution of the image resolution (1 m). (ii) The braiding index is likely to be underestimated because the number of channels on the maps depends on the cartographer's interpretation (PEIRY, 1988; MIRAMONT, 1998). Channels that occasionally accomodate water are not always taken into account and can therefore be underestimated. Despite these inaccuracies, this analysis of the maps provides an order of magnitude/frequency with regards to the rate of hydromorphological variations during a period of hydroclimatic transition.

Mapping choices had to be made to establish the diachronic zoning of the Isonzo floodplain. We simplified the zoning process by only working on the black and white shots because of the loss of information in the colour photos. Although the Austrian maps show an accurate typology of natural surfaces, we have not included this level of detail because it was absent in the subsequent documents. We therefore chose the zoning permitted by the less detailed map (1806) by identifying the riparian forest, the gravel bars, and the farmed areas. The resulting maps are compiled in fig. 7.

2.3 - Hydro-morphometric variables

Using the resulting maps, we have chosen to measure a series of morphological parameters commonly used in studies dealing with torrential dynamics (SURIAN, 1999; WARD *et al.*, 1999; WARNER, 2000). The sinuosity index is the ratio of the thalweg length to the distance between two inflection points in the valley. In the braided channels, we chose to adopt the method described by BRICE (1964), by measuring the sinuosity of the active-channel axis. The braiding index proposed by PEIRY (1988) is the sum of the different arms of the river reported to the active-channel length. The braiding and sinuosity indices move in the opposite direction (MIRAMONT, 1998). The active-channel width was also calculated. All measurements were made for each KP.

3 - Results

3.1 - Active-channel narrowing: A continuous phenomenon

Active-channel narrowing of the Isonzo River is observed during the last 200 years (fig. 7). During the 20th century, the active-channel width was reduced by 10 m on average. The narrowing of the active channel is particularly pronounced between the KP 22 and KP 12 from 1806 to 1880, and between the KP 26 and KP 19 from 1938 and 1954. Meanwhile, the area of Marcorina experienced a severe active-channel narrowing (820 m in 118 years) between 1880 and 1998, following the cut-off of the Colussa meander (KP 9-12; fig. 8 A and B).

We brought these values in m/a and adopted a series of time windows that allows us to measure the rate of the active-channel narrowing of the Isonzo River between key dates (fig. 9). We chose the periods 1806-1880, to characterise the channel behaviour at the end of the LIA, 1880-1938, and 1938-1998 during which the hydroelectric dams were built. (i) Between 1806 and 1880, the active-channel was narrowed between the KP 22 and KP 12, due to the gradual embankment of the river and farming on the flood plain. Two sectors, between the KP 26 and KP 23 and between the KP 11 and the river mouth, experienced a widening of the active-channel, the first one due to the deposition of median bars in the context of abundant bed-load supply and a decrease in energy due to a gentler slope, the second one because of the growing of meanders. (ii) Between 1880 and 1938, only the sector between the KP 12 and the river mouth is characterised by an active-channel narrowing. Indeed, the meander between the KP 12 and KP 8 was cut-off. Finally, the channel avulsion of the Isonzo towards the Quarrantia involves the narrowing of the ancient river mouth. (iii) Between 1938 and 1998, the narrowing of the active channel can be generalised to the entire study area,

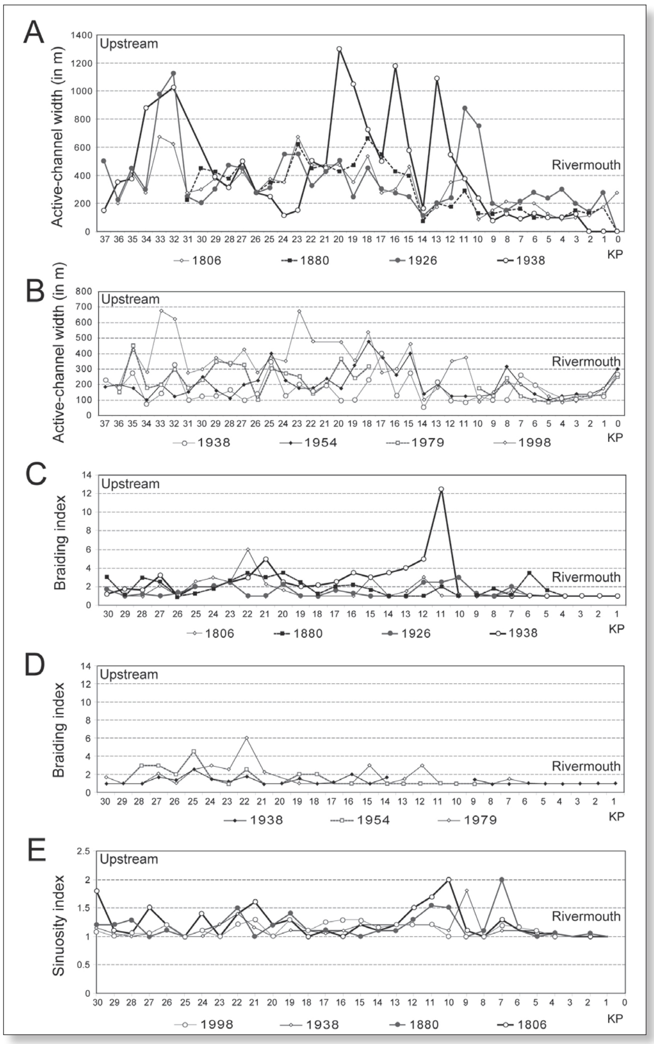

Fig. 8 – Dynamics of the Isonzo active channel since the beginning of the 19th century. Absolute variations of the active-channel width between (A) 1806 and 1938 and (B) 1938 and 1998. Evolution of the braiding index between (C) 1806 and 1938 and (D) 1938 and 1979. (E) Evolution of the sinuosity index between 1806 and 1998.

except around the 8 km mark where the slight widening of the active-channel is due to the reactivation of the Sdobba channel, after the artificial closing of the Quarrantia channel in 1937.

3.2 - Reduction of the braiding index

The braiding phenomenon is related to the combination of an abundant bed load, strong bank erodibility, and high values of specific stream power (SCHUMM, 1977). For the Isonzo River, the braiding index (fig. 8C and D) decreased between 1806 and 1880. Secondary channels were abandoned before their canalisation in order to irrigate the agricultural lands and supply water to the mills. Braiding continued between 1880 and 1938 with local variations due to the migration of median bars in the active channel. Over the last 60 years, the disappearance of braiding became an effective phenomenon along the Isonzo River, especially between 1938 and 1954.

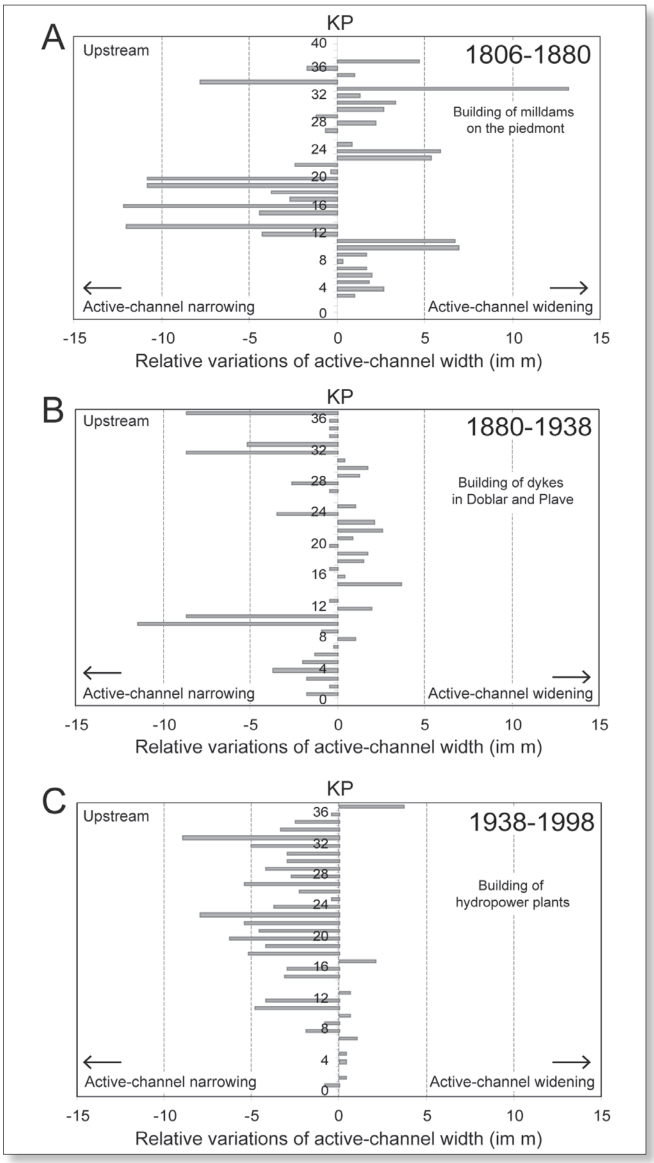

Fig. 9 – Relative variations of the Isonzo active-channel width during the periods 1806-1880 (A), 1880-1838 (B), and 1938-1998 (C) according to kilometric points in the piedmont and the coastal plain.

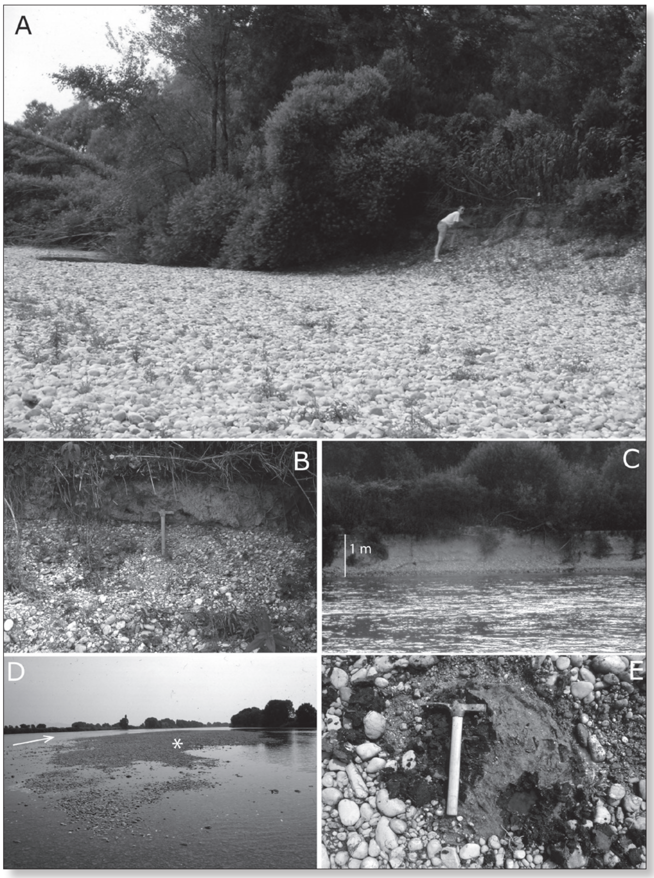

Fig. 11 – Stratigraphical evidence of active-channel narrowing of the Isonzo River. (A) The left bank of the Isonzo River downstream of the Pieris Bridge (photo: G. Arnaud-Fassetta, August 1999), developed thanks to the incision and the narrowing of the post-LIA active channel. The trees of the riparian forest, toggled within the channel, also attest to the incision of the active channel and the erosion of the riverbank. The scale is given by V. Bresson. (B) Stratigraphic section on the left bank of the Isonzo River downstream of the Pieris Bridge (photo: G. Arnaud-Fassetta, August 1999). The section shows coarse (pebbles) deposits (bed load) covered by fine (sandy silt) deposits (flood-plain deposits; the hammer provides scale). This phenomenon expresses (i) the incision and (ii) the narrowing of the post-LIA active channel. (C) The right, concave bank of the Isonzo channel downstream of the Torre confluence (photo: I. Siché, 2005). Pebbles and gravel present at the base of the stratigraphic section correspond to channel or bar deposits that the river erodes. In this part of its course, the Isonzo River has migrated laterally over 2 km in 150 years and incised its channel by about 1.2 m. (D) The active channel of the Isonzo River downstream of the Isola Bridge (photo: G. Arnaud-Fassetta, August 1999). The gravel/pebble bars are thin (10-20 cm), and the old flood-plain deposits (peat) are sometimes exposed on the channel floor (see fig. 11E). The flow direction and location of fig. 11D are denoted by the arrow and the asterisk, respectively. (E) Detailed view of peat (ancient flood-plain deposits) under the current pebbles (bed load) of the Isonzo River downstream of the Isola Bridge (photo: G. Arnaud-Fassetta, August 1999). The exposure of peat is related to channel incision.

3.3 - Substitution *vs.* maintenance of the sinuous channel pattern

The evolution of sinuosity has other shades (fig. 8E). The sinuosity index was down between 1806 and 1880 by about 0.5 point. It decreased slowly between 1880 and 1938 then between 1938 and 1998, even if it increased between the KP 25 and KP 14 during the last period. Indeed, the photo-interpretation indicates that in the studied sector, the braided channels give way to a sinuous, gravel channel. We can relate this phenomenon to the combination of two factors: (i) the incision of the Isonzo channel in its piedmont, which reduced the lateral mobility of the river; and (ii) artificial cut-off, channelization and river embankment.

3.4 - Active-channel incision

The Isonzo River is known to be incising the alluvial floor at least since the 1950s. CANZIANI (1980) conducted a survey of erosion points in the Isonzo channel, which correspond to bank cuts and scours at the base of bridge piers. These processes are still taking place today: the Pieris railway bridge, shot in 1979 and 2000, shows net erosion at the base of the bridge piers (fig. 10 B and C). The same phenomenon is observed at the base of the Pieris road bridge. Our own field data indicate that for the Pieris sector the active channel of the LIA is now incised by ~1 m while the present active channel is significantly narrowed (fig. 11 A to C). The bed load has significantly decreased, with a Q_l/Q_s ratio that is favourable to the incision of the alluvial floor. The bed load was even totally eroded when the stream power was sufficient to erode gravel and pebbles in the channel bottom. In this case, the very thin layers of bed load overlie the Holocene peat deposits (fig. 11 D and E).

4 - Discussion: Causes of the 'fluvial changes'

The parameters responsible for the fluvial changes of the Isonzo River involved the whole catchment and resulted from a decrease in both sediment supply and river discharge.

4.1 - Continuous decrease in sediment supply

Hydroclimatic variability mainly controlled the fluvial changes before the period of large hydraulic works in the Isonzo valley. However, we may invoke human activities to explain the narrowing of Isonzo's active channel between the KP 34 and KP 16. Sediment retention in the piedmont prevents its deposition on the coastal plain, and therefore the channel aggradation and lateral migration. This phenomenon is true at all stages of the sediment transit, but differs according to the transport modes:

- (i) Decrease in the suspended load: Fine-grained sediment supplies are derived from the piedmont by bank undercutting and the mountain affected by landslides and gully erosion (*e.g.*, silts and sands observed in the channel of the Soča Riverin Bovec, supplied by slope erosion). Fine-grained sediments are also derived from the emptying of clay pockets in the dolomites (*e.g.*, in November 2000, the emptying of a clay pocket of 1.5 million m^3 was discharged into the Koritniča River, a tributary of the Isonzo River in the upper catchment; the Koritniča channel aggraded of 1.8 m in a month). The fine sediments are not retained in significant amounts by hydroelectric dams and milldams because they constitute a load mainly transported by suspension. The transport of a fine sediment load (clay, silt and sand) is therefore much affected by the hydraulic structures. But their overall volume decreased due to slope restoration. For 50 years, the PUH has developed a reforestation programme initiated by the Austrians, and the rate of forest coverage in the mountains is now up to 75%. Slope stabilisation and the mitigation of soil erosion have further reduced the fine sediment yield supplied in the Isonzo floodplain. This phenomenon could affect the river competence, which depends on bed shear stress and the percentage of fine particles in the river flow (LIÉBAULT *et al*., 2012).

- (ii) Recent bed-load retention in dam reservoirs: the petrography of bed sediments certifies that the gravel and pebbles come from the entire Isonzo catchment (MAROCCO, 1994; BAVEC, 2001; BRESSON, 2001). In the mountain, the sediment source of bed load is mainly produced by deposits mobilized during rock-wall collapses, more than weathering. Bed-load transit, discontinuous in time and space, is particularly efficient during powerful flood events when the specific stream power and bed shear stress exceed the critical values (SICHÉ, 2002). In the middle part of the Isonzo catchment, the transit of bed load has been disrupted by the presence of three hydroelectric dams, which trap coarse sediments (*e.g.*, an aggradation of 5 m was observed in the Soča active-channel upstream of the Doblar dam between 1938 and 1982; CANZIANI, 1980; SICHÉ, 2008). If the bed load is sometimes re-injected into the active channel at the opening of each of the first two dams (Doblar, Plave), it is permanently trapped in the third one (Solkan; fig. 5).

Finally, the solid discharge of the Isonzo River has steadily decreased during the 20th century, mainly due to anthropogenic actions in the catchment (mountain reforestation, gravel extraction in the channel, retention of bed-load by hydroelectric dams, channelization). Without measurement projects in the early 20th century, it is unclear whether the decrease in sediment discharge was already effective in 1880. However, bed load has certainly decreased sharply since the construction of dam reservoirs.

4.2 - General and local disturbances of river discharge

The drastic decline in the volume of sediment transported as bed load is a key factor in driving the 'fluvial changes' of the Isonzo River. It is also important to note that the intra-annual distribution of rainfall volume has also changed during the 20th century.

- (i) Post-LIA climate change and modification of flood regime: We first sought from the climate control in the process. For this, we determined the occurrence of each type of discharge with the data series available at the Solkan station in the upper catchment of the Isonzo River. We chose a threshold of 30 m^3/s below which we record 80% of mean daily discharges. Figure 12B shows the frequency of occurrence of discharge beyond this threshold, similar to the bankfull discharge. We note that the occurrence of low discharge (both minimum and moderate values) appear to be declining over the

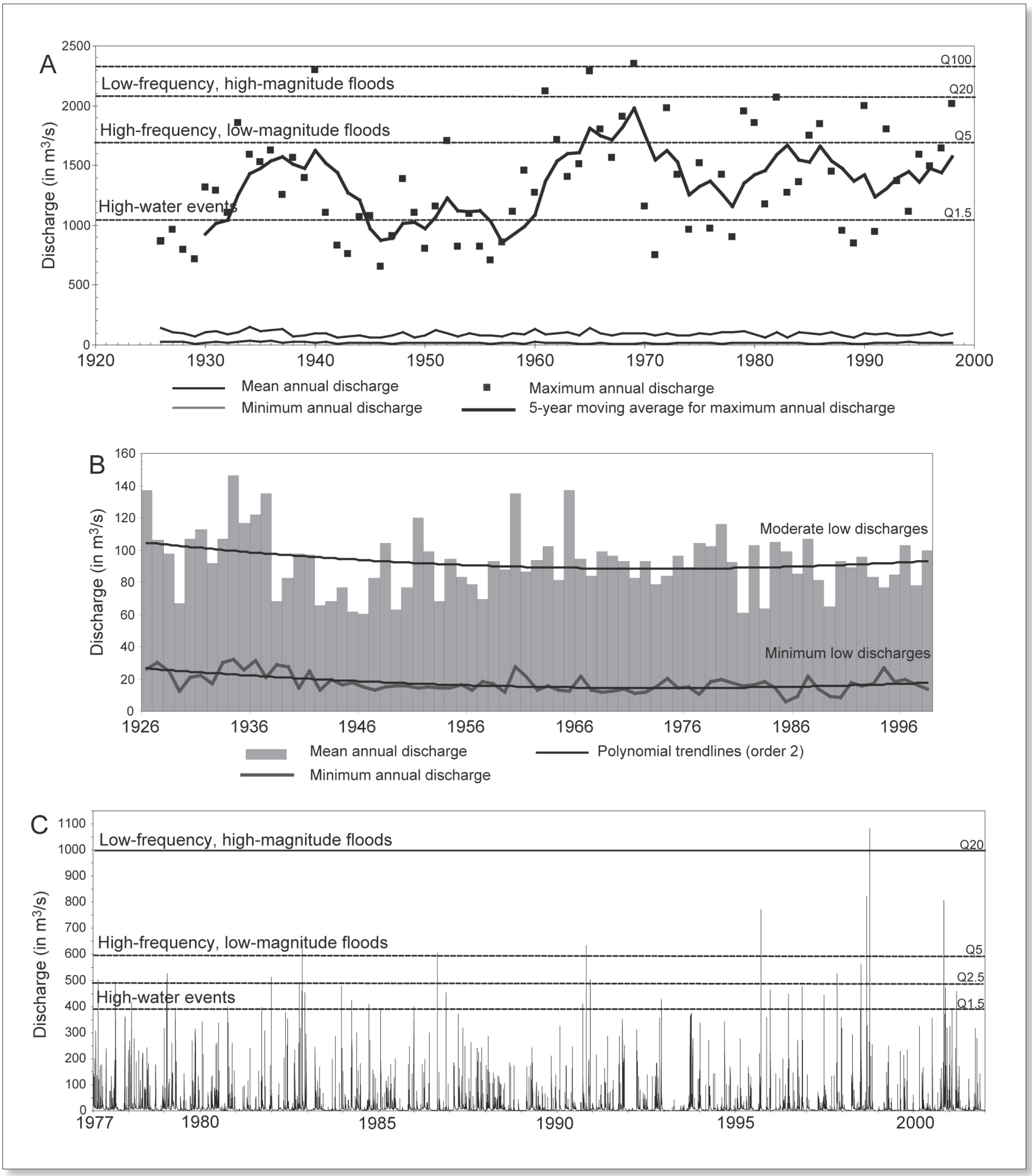

Fig. 12 – Evolution of annual discharges of the Natisone River in Cividale (data: Ufficio idraulica) and the Isonzo River in Solkan (data: ARSO). (A) Average monthly discharge and annual minimum discharge of the Isonzo River in Solkan (1926-1998). (B) Annual discharge of the Isonzo River in Solkan (1926-1998). (C) Daily discharge of the Natisone River (1977-2006).

course of the 20th century. In addition, we observe a significant change concerning the magnitude and frequency of flood events (fig. 12A), which were classified into three groups: (G1) flood events with RI comprised between 5 and 20 years]Q_5-Q_{20}]; (G2) flood events with RI comprised between 20 and 100 years] Q20-Q100]; (G3) >100-year RI flood (>Q100). From 1926 to 1960 (34 years), the distribution of flood events is: G1=2; G2=1; G3=0. From 1961 to 1970 (10 years), both the magnitude and frequency of flood events increases, with G1=4; G2=2, and G3=1. From 1970 to 1998 (30 years), we observe a decrease in extreme flood events but an increase in large floods, with: G1=0; G2=8; G3=0. The same phenomenon is recorded in the Natisone River (fig. 12C), where large floods have become more frequent since the 1970s. We invoke climate change after the end of the LIA, since 1860. Firstly, the lower frequency of rainfall and global warming during the first part of the 20th century. have not only promoted biostasy on the slopes but also decreased the amount of water received by the catchment (SICHÉ, 2008). This could be one explanation for the reduction in the number of channels and amphibious areas in the piedmont and the coastal plain. Secondly, although there have been fewer exceptional hydrological events during the past 30 years, the moderate-to-high flood events, particularly morphogenous, are more frequent.

- (ii) Local perturbations by dams during the last 100 years: Flow disturbances do not affect the total volume of water, as diversion channels for the use of hydropower plants and factories re-inject the water they have taken. But the milldams in the piedmont locally affect the specific stream power of the river by locally increasing the water line by about 1 m and the hydraulic gradient downstream (SICHÉ, 2008). Downstream of the structures, this explains the channel incision, bank undercutting and erosion of bridge piers (fig. 10 B and C). Therefore, despite the general context of decreasing flood magnitude, the decrease of bed load and the artificial, local increase in the specific stream power by structures mean that human activities have greatly accelerated the process of channel incision and narrowing initiated at the end of the LIA.

In summary, the severe reduction of braiding may have been initiated during the end of the LIA, but it has dramatically accelerated since 1938, with the building of the hydroelectric dams and gravel extraction. A decrease in the braiding index is thus the result of the decrease in sediment supply (Q_s-) compared to the decrease of discharge (Q_l-), according to the relationship Qs->Q_l-. After 1960, the active-channel width of the Isonzo River continued to decrease despite the increase in flood frequencies. However, in this context of sediment shortage, the critical stream power of the Isonzo River remained sufficient to allow it to incise its active-channel by destruction of bed-load armouring. In some fluvial areas where riverbanks are not protected by structures (dykes, stream banks), the river dissipates its energy by eroding its banks. This phenomenon is not dominant at the catchment scale and does not affect the general trend of channel narrowing. Its effects are not only related to the autocyclic adjustment of riverbeds (*i.e.*, offset between the bed-load deficit by the erosion of riverbanks) but also due to anthropogenic forcing (*i.e.*, reduction of areas of flood dissipation due to channelization). This phenomenon has been demonstrated in other Alpine catchments, including the Guil River (ARNAUD-FASSETTA and FORT, 2004). The decline in the braiding and sinuosity indices of the Isonzo River in the piedmont fits into the evolution model of most Alpine rivers modified by human activities since the end of the LIA (BRAVARD and PEIRY, 1993; BRAVARD *et al.*, 1997; LIÉBAULT and PIÉGAY, 2002).

5 - Conclusions

The Isonzo River experienced a 'fluvial metamorphosis' beginning at the end of the LIA, but especially during the first part of the 20th century. Therefore, the evolution of its active channel followed that observed in other Alpine streams (fig. 13). Channel changes in the piedmont and the coastal plain of the Isonzo River is related to a combination of factors involving human activities in the channel and the catchment along with, to a lesser extent, the post-LIA climate change. The timing and terms of this metamorphosis are found in other rivers of the Padan Plain, such as the Piave River (SURIAN, 1999), and other European rivers, such as the Siret River in Romania (SALIT *et al.*, in press) or the Rhône River in Switzerland (LAIGRE *et al.*, 2009).

Thus, in the Isonzo River, the active-channel and the flood plain have continued to narrow. Until 1938, braided channels dominated in the piedmont and the meanders developed on the coastal plain. During the second half of the 20th century, the meanders disappear almost completely by artificial cut-off or avulsion. The braiding is considerably reduced and the Isonzo River develops a sinuous gravel channel (upstream) then a sub-straight, sandy channel (downstream). The active-channel width decreases between -100 m and -2000 m, and the braiding and sinuosity indices decrease between 1 to 3 points. This trend is mainly controlled by climate conditions until the early 20th century as (i) the number of exceptional flood events seem to decrease and (ii) it affects both the natural part of the upper basin and the human-modified piedmont (SICHÉ, 2008). Thereafter, hydraulic structures built on the floodplain supported the effects of climate change. Indeed, embankments and Mussolini's land reclamation projects significantly contributed to reduce the flood-plain area and simplify the channel morphology. The milldams and hydroelectric dams built in the active channel played a key role in driving the fluvial changes by disrupting the bed-load transit. The decrease in bed-load transport is mainly expressed through incision of the active-channel in the piedmont, which began at the end of the 19th century and prevailed until the early 1980s. During the past 20 to 30 years, the nature of the hydroclimatic hazard has changed. If the erosion of bridge piers seems to generally be on the decrease (SICHÉ, 2002), the undercutting of riverbanks is a recurrent problem associated with the armouring of the channel bottom. Bank undercutting induces the building of bank-protection structures, which in turn accentuate the energy of the channel and the erosion of riverbanks in the downstream areas not yet equipped. In the near future, if the dams planned in Slovenia may further reduce the bed-load transit, they are also likely to worsen the lateral erosion of the Isonzo active channel in the piedmont. In the end, the main problem lies in the management of the 'fluvial metamorphosis' and its associated processes, which are still poorly understood by international river managers and users. Sharing the catchment between two countries seems to curb the cooperation that is necessary to plan for the future.

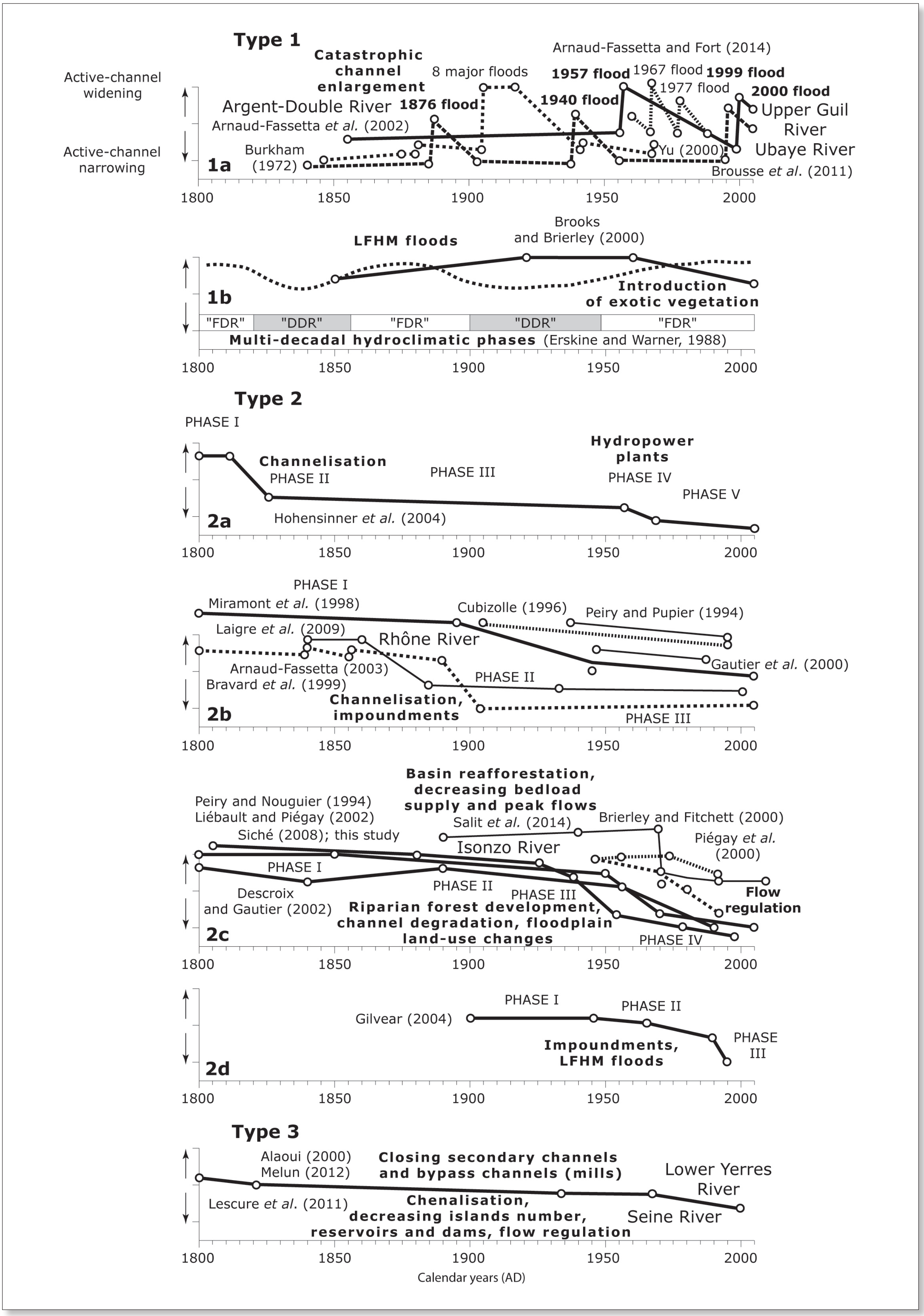

Fig. 13 – The Lower Isonzo River: its hydromorphological behaviour was largely influenced by human activities, which completes the typology (Type 2c) of the floodplains (after Arnaud-Fassetta and Fort, 2014).

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