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ORNELLA TURITTO (*), MARCO BALDO (*), CHIARA AUDISIO (*) & GIORGIO LOLLINO (*)

A LiDAR APPLICATION TO ASSESS LONG-TERM BED-LEVEL CHANGES IN A COBBLE-BED RIVER: THE CASE OF THE ORCO RIVER (NORTH-WESTERN ITALY)

ABSTRACT: TURITTO O., BALDO M., AUDISIO C. & LOLLINO G. - *A LiDAR application to assess long-term bed-level changes in a cobble-bed river: the case of the Orco River (North-Western Italy).* (IT ISSN 0391-9838, 2010).

The technique of terrestrial or airborne LiDAR (Light Detection And Ranging) has recently provided many topographic data at high accuracy and speed in various kinds of applications as urban planning, forest inventory, coastline protection, flood hazard forecast, glacier, avalanche and landslide monitoring. In the topic of fluvial investigations the LiDAR technique has provided useful information on river morphology. In particular, starting from a first Digital Terrain Model (DTM) generation, the following LiDAR surveys have allowed every smallest morphological adjustment to be assessed. They also allowed an accurate quantification of erosion and deposition processes which occurred in the river bed, deduced by an assessment of altimetric and volumetric changes, on a time scale of some days, some months or some years (short-term investigations).

The great potential of the data acquired by LiDAR suggested a different and particular use: to test a method which can provide an assessment of the incision occurred in a cobble-bed river on a time scale of the last 100 years (long-term investigation).

The study case refers to the Orco River (906 km^2 of drainage basin), an Alpine tributary of the Po River in North-Western Italy. Its channel morphology underwent a severe transformation above all in the second half of the 20th century, mainly due to human interventions. In a 25 km reach the channel width decreased down to 44% on average from 1954 to 1989 and the multi-thread original pattern turned towards the single-thread pattern. Moreover, the stereoscopic analysis of aerial photographs also showed vertical changes, induced by the river bed incision, but the lack of previous topographic data did not allow to quantify its extent.

In 2003 a detailed DTM of the Orco River was generated by an airborne LiDAR acquisition. In addition to the present river course this DTM covered the surrounding floodplain with relic forms of the older channel positions. These forms are identified and dated thanks to historical maps and aerial photographs. This particular circumstance suggested the use of this DTM to test the method for the assessment of the occurred channel incision. In a selected river reach (3.5 km long) six topographic cross-sections were drawn so as to cross the present and the older river positions. The river incision was obtained as a difference between the recent and the previous mean levels of its bed. A bed level incision of 2.7 m on average came out; the maximum (more than 3 m) was found near a narrow bridge and the minimum (2 m) was found where the river had a wider space for its planimetric mobility.

KEY WORDS: LiDAR technique, Channel incision, Cobble-bed river, Orco River, North-Western Italy.

RIASSUNTO: TURITTO O., BALDO M., AUDISIO C. & LOLLINO G. - *Un'applicazione della tecnica LiDAR per valutare le variazioni altimetriche di un alveo fluviale ciottoloso nel lungo termine: il caso del Fiume Orco (Italia nord-occidentale).* (IT ISSN 0391-9838, 2010).

La tecnica LiDAR (Light Detection And Ranging), con strumento terrestre o aviotrasportato, ha recentemente permesso di acquisire numerosi dati topografici ad alta precisione e con rapidità in vari campi di applicazione, come nella pianificazione urbanistica, nel censimento forestale, nella protezione di coste, nella previsione del pericolo di piena, nel monitoraggio di ghiacciai, valanghe e frane. Nel campo degli studi sulla rete idrografica la tecnica LiDAR ha fornito utili informazioni sulle caratteristiche morfologiche dei corsi d'acqua. In particolare, a partire da una prima generazione di Modello Digitale del Terreno (DTM) successivi rilievi LiDAR hanno permesso di verificare i più piccoli cambiamenti morfologici. Si è così ottenuta anche un'accurata valutazione dei processi di erosione e deposito in alveo – dedotti dalla quantificazione delle variazioni altimetriche e volumetriche riscontrate – nella scala temporale di alcuni giorni, alcuni mesi o alcuni anni (indagini a breve termine).

Le grandi potenzialità dei dati acquisiti tramite LiDAR ne hanno suggerito un differente e particolare uso: testare un metodo in grado di fornire una valutazione dell'incisione subita negli ultimi 100 anni da un alveo a fondo ciottoloso (indagine a lungo termine).

Il caso di studio si riferisce al Fiume Orco (906 km^2 di bacino idrografico), tributario alpino del Fiume Po nell'Italia nord-occidentale. La

(*) *Consiglio Nazionale delle Ricerche - Istituto di Ricerca per la Protezione Idrogeologica (CNR-IRPI) Strada delle Cacce, 73 - 10135 Torino.*

This research began in the context of the MIUR-PRIN 2005 Project «Present and recent dynamics of river channels in Northern and Central Italy: evolutionary trends, causes and management implications» (national co-ordinator: N. Surian, University of Padua; local co-ordinator: L. Pellegrini, University of Pavia) and has gone on in the context of the MIUR-PRIN 2007 Project «Present evolutionary trends and possible future dynamics of alluvial channels in Northern and Central Italy» (national co-ordinator: N. Surian, University of Padua; local co-ordinator: G. Lollino, CNR-IRPI of Turin). We thank N. Surian for the careful reading of the manuscript and for his helpful suggestions. Thanks are also due to Prof. D. Hartley for the revision of the English text and to the anonymous referees for their helpful reviews.

morfologia del suo alveo ha subito una profonda trasformazione soprattutto nella seconda metà del XX secolo, dovuta in massima parte all'intervento antropico: dal 1954 al 1989 su un tratto fluviale di 25 km la larghezza dell'alveo si è ridotta del 44% in media e l'originario modello fluviale a più canali di deflusso si è modificato in forme di transizione verso il singolo canale. Inoltre, l'analisi di riprese aerofotografiche in visione stereoscopica ha posto in evidenza anche variazioni altimetriche dell'alveo, dovute all'abbassamento del suo fondo, ma la mancanza di dati topografici pregressi non ha permesso di quantificarne l'entità.

Nel 2003 era stato generato un dettagliato DTM del Fiume Orco, ottenuto da LiDAR elitrasportato. Oltre all'attuale percorso fluviale, il DTM copriva anche la circostante piana inondabile dove sono presenti le forme relitte delle posizioni occupate dal corso d'acqua nel secolo scorso, identificate e datate sulla base di documenti storici, cartografici e aerofotografici. Questa particolare circostanza ha suggerito l'uso del DTM per testare il metodo di valutazione dell'abbassamento subito dall'alveo: su un tratto campione di 3,5 km sono state acquisite sei sezioni topografiche tracciate in modo tale da intersecare l'attuale e le storiche posizioni del fiume. È stata quindi misurata l'entità di approfondimento come differenza tra le quote medie dell'attuale e del precedente fondo alveo. Ne è emerso un valore di incisione del fondo pari a 2,7 m in media, con un massimo di oltre 3 m in corrispondenza di uno stretto ponte e un minimo di 2 m dove il fiume disponeva di un più largo spazio per la sua mobilità planimetrica.

TERMINI CHIAVE: Tecniche LiDAR, Incisione d'alveo, Alveo a fondo ciottoloso, Fiume Orco, Italia nord-occidentale.

INTRODUCTION

Rivers naturally adjust their channel geometry, mainly through their discharge and sediment load, which are the driving variables depending on the physiographic and hydrologic conditions of the whole drainage basin (Hey, 1997). The processes of sediment erosion, transport and deposition produce some characteristic channel morphologies (patterns), classified in international literature as straight and meandering in single-thread rivers, braiding and anastomosing in multi-thread rivers, even if intermediate and transitional forms occur most frequently (Thorne, 1997).

In the past, human interventions have often induced a severe river channel instability, altering both discharge and sediment transport. In some cases they have modified the natural channel form and size, with dangerous consequences for private and public properties placed inside or near the rivers (Gregory, 1987; Bravard & *alii*, 1999).

The negative human role in preventing geomorphic processes has been the focus of national and international researches (see, e.g., Smith & Winkley, 1996; Liébault & Piégay, 2001; Liébault & Piégay, 2002; Rinaldi, 2003; Surian & Rinaldi, 2003). Some works published in recent special issues (Borgatti & Soldati, 2005; James & Marcus, 2007) have specifically faced the problem of the human impact on several fluvial systems. From these researches human influence in the processes of channel form modifications came out. An important role has been played by dam constructions and irrigation diversions, but above all by fluvial regulation works and gravel mining, extensively increased after the 1950s.

In particular, human encroachment has induced on many rivers of Northern and Central Italy widespread processes of severe channel narrowing over the last 200 years, even reaching 70-80% in several cases (Surian & *alii*, 2009a). Such processes, also favoured by channel incision (up to 8÷10 m over about the last 100 years), almost everywhere led to a rapid transformation of the original channel morphology. The multi-thread channels turned into transitional (wandering) or even single-thread channels above all between the 1960s and the 1980s (e.g. Pellegrini & *alii*, 1979; Castiglioni & Pellegrini, 1981; Bezoari & *alii*, 1984; Maraga, 1989; Canuti & *alii*, 1992; Surian & Rinaldi, 2003; Surian & Rinaldi, 2004; Surian, 2006; Surian & Cisotto, 2007; Pellegrini & *alii*, 2008; Rinaldi & *alii*, 2008; Surian & *alii*, 2008).

For several of these rivers the investigation on channel planform changes has been made easier thanks to a good availability of hydrographical configurations taken from historical maps and aerial photographs and superimposed by GIS procedures. Whereas, the investigation on bed level changes has not always been possible for the lack of the previous topographic data. Even if the stereoscopic analysis of aerial photographs and the field survey have provided some indications on bed level changes, they sometimes correspond to qualitative and not quantitative information.

This is the case of the Orco River, an Alpine tributary of the Po River in North-Western Italy. It featured a channel incision, clearly shown by the stereoscopic view of aerial photographs taken at various dates. No previous topographic data, however, are available to compare and quantify its extent. To attempt a solution of this gap, we have resorted to the Light Detection And Ranging (LiDAR) technique.

Recent studies show that different techniques using the terrestrial or airborne LiDAR proved a useful tool for the control of the land surface variability in various kinds of applications as urban planning, forest inventory, coastline protection, flood hazard forecast, glacier, avalanche and landslide monitoring (e.g. Deline & *alii*, 2004; Broccolato & *alii*, 2006; Chen & *alii*, 2006; Whitworth & *alii*, 2006; Kwak & *alii*, 2007; Deronde & *alii*, 2008; Young & Ashford, 2008). In the topic of fluvial investigations LiDAR techniques have also provided much information on river morphology, bathymetry and channel changes (e.g. Charlton & *alii*, 2003; French, 2003; Heritage & Hetherington, 2007; Hilldale & Raff, 2008; Notebaert & *alii*, 2009). Further researches have specifically focused on altimetric data variations to estimate volumetric channel changes, too: starting from a first survey they allowed to quantify the following erosion and deposition processes occurred over some days, some months or some years with a high degree of precision (e.g. Lane & *alii*, 2003; Milan & *alii*, 2007; Lollino & *alii*, 2008). These techniques were specifically used to know every significant change of the river morphology on a small time scale by steps corresponding to the subsequent surveys (short-term investigations towards the future).

With regard to the Orco River, a detailed Digital Terrain Model (DTM) by an airborne LiDAR was generated in 2003 to know the river bed elevation reached after a severe flood. Some LiDAR acquisitions were repeated in the following years to monitor the future increases/decreases of the bed level and quantify both erosional and depositional processes through the assessment of volumetric channel changes (Lollino & *alii*, 2005a; Lollino & *alii*, 2005b; Lollino & *alii*, 2007). In addition to the present river course, this DTM covered the surrounding floodplain with relic forms of the older channel positions (occupied over the last 100 years), identified and dated thanks to historical maps and aerial photographs. This particular circumstance, together with the very high density and accuracy of the point data provided by LiDAR, suggested the use of the 2003-DTM to test a new method for morphological investigations: in a selected river reach (3.5 km long) six topographic cross-sections were drawn so as to cross the present and the older river positions. From these cross-sections the river bed incision was assessed as a difference between its recent and previous mean levels.

Compared with conventional LiDAR applications, this approach represents a new path of investigation and an opposite point of view (long-term investigation towards the past). Against the usual methods, however, our kind of application may be adopted only when and where a larger margin of error in measurements can be accepted. In this paper methods and results of our experience are presented.

STUDY CASE

The Orco River flows from the Alps (maximum elevation, Becca di Moncorvè, 3 865 m a.s.l.) and discharges in the Po River (minimum elevation, 177 m a.s.l.) near Chivasso, a town in the Turin Province (fig. 1). It drains an area of 906 km^2, 617 km^2 of which develop in the mountain basin closed at the Pont Canavese hydrometrical gauging station (gauge datum 430 m a.s.l.). Its channel is 83 km long, 47 km in the mountain basin and 36 km in the plain where it incises an old alluvial fan and, near its mouth, the Po alluvial plain (tab. 1). In the plain the river channel has a mean slope of 0.7% and is modelled mainly into cobbles and coarse gravel with a D_{50} ranging between 17 cm in the upper plain and 6 cm in the lower plain (Bianco & *alii*, 2005).

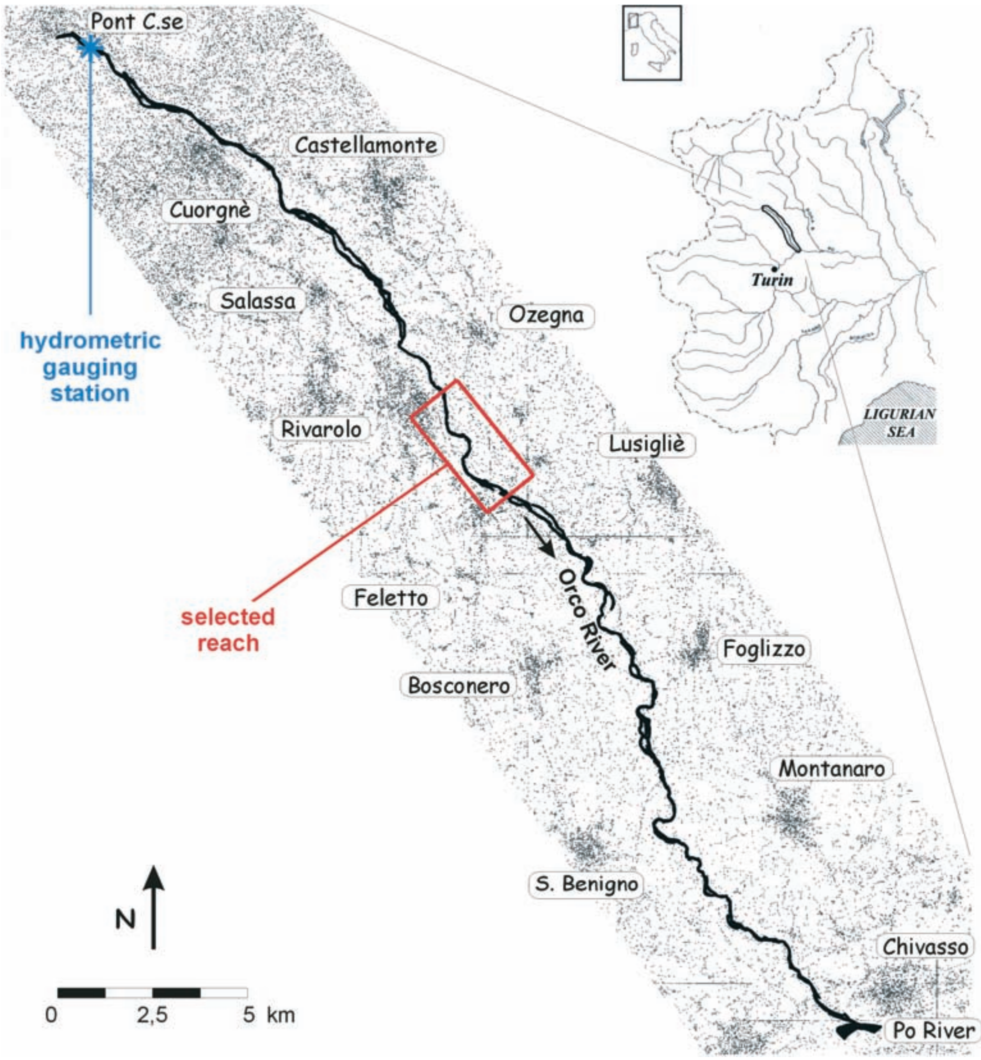

FIG. 1 - General setting of the Orco River in North-Western Italy and location of the selected reach.

TABLE 1 - Main physiographic and hydrologic characteristics of the Orco River. Discharges measured at Pont Canavese gauging station (617 km^2 of drainage area)

drainage basin area (km^2)	mountain basin (km^2)	max/min elevations (m a.s.l.)	channel length (km)	channel length in the plain (km)	mean slope in the plain (%)	max/min D_{50} of bed sediments in the plain (mm)	mean annual precipitations (mm/yr)	mean annual discharge (m^3/s)	last and previous max peak flood discharges (m^3/s)
906	617	3865/177	83	36	0.7	170/60	1250	20	1650 Oct. 2000 1500 Sept. 1993 1410 Sept. 1947

In 2005 a research on channel planform changes of an Orco River reach (25 km long in the middle-lower plain) provided much information on pattern characteristics and on variations of its dimension and position over the last 200 years (Turitto & Audisio, 2005; Pellegrini & *alii*, 2008). From this research natural and man-induced causes of the main changes have also been identified. Information has come out from published and unpublished documents, historical maps dating from the beginning of the 19th century and aerial photographs taken every decade from 1945 until 2003. Through GIS procedures the different channel positions have been superimposed over the Regional Technical Map on a 1:10 000 scale as a base layer. The widths of each total channel (including low-water channel/s, bars and islands) and each active channel (excluding islands) have been measured (every 100 m along the fluvial axis) and compared (fig. 2). The difference between the two kinds of width is very important since they can show the adjustments occurred in the configuration of the whole fluvial system (the total channel) or only of the low-flow channel/s with bare/sparsely vegetated bars (the active channel) (Thorne, 1997, p. 204).

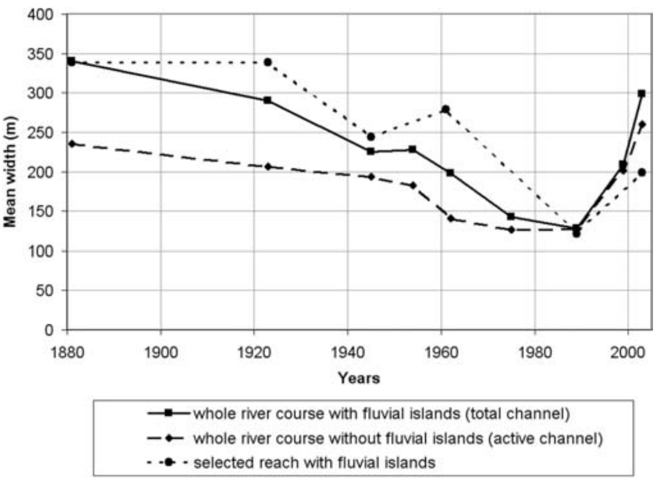

FIG. 2 - Temporal trends of the mean width of the «total channel» (with islands, continuous line) and the «active channel» (without islands, broken line) of the 25 km Orco River reach over the 1881-2003 period. The diagram also shows the trend of the mean width of the total channel coming from the six cross-sections of the selected reach (dotted line, see the last line in table 3).

With regard to the accuracy of such measurements, the maximum error was estimated less than 20 m on the oldest maps and 5÷6 m on aerial photographs, according to some previous and similar works (Downward & *alii*, 1994; Winterbottom, 2000; Liébault & Piégay, 2001; Rinaldi, 2003; Hughes & *alii*, 2006; Cencetti & Fredduzzi, 2008). Therefore the margin of error is acceptable for the accuracy needed by our study, concerning width changes of hundreds of metres over a long period.

Historical channel changes

Channel-width changes

During the 19th century the river channel showed almost everywhere a multi-thread morphology with widths and numbers of ramifications variable both in space and time. A progressive simplification of fluvial configuration, however, was already observed from the end of the 19th century. This process, largely due to natural phenomena and only locally to human interventions as bridge building (Turitto & Audisio, 2008), lasted until the first half of the 20th century (–33% of the total channel width in about 70 years from 1881 to 1954). After the 1950s the process underwent an acceleration (–44% of the total channel width in about 30 years from 1954 to 1989), both because of the abandoning of secondary ramifications and the islands joining the surrounding floodplain. The result of this rapid evolution led to a drastic and widespread transformation of fluvial patterns: the multi-thread or transitional channel turned into a sinuous-meandering channel (see the 1954 and 1975 channel configurations in fig. 3).

The causes of these morphological changes were mainly due to the channel regulation works, started after World War II, to close off peripheral branches or cross the river by new bridges. The most severe human impact, however, was produced by the widespread and uncontrolled in-channel sediment dredging needed for road and building constructions. In 1975 the gravel mining encroached on about 60% of the total channel surface up to a remarkable but not quantified depth.

Bed-level changes

The transformation towards a single-thread channel started in the lower plain and proceeded towards the up-

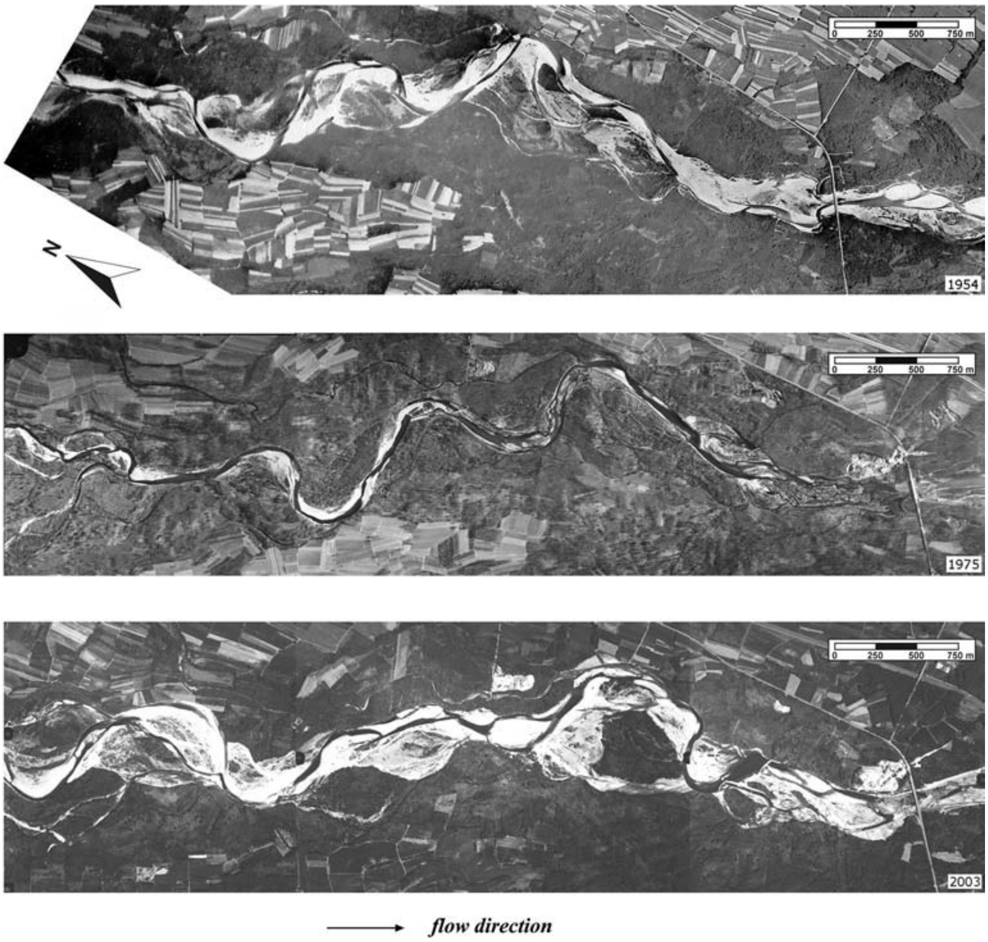

FIG. 3 - The Orco River near the town of Foglizzo. The aerial photographs clearly show the channel pattern modifications: the heavy narrowing that occurred from 1954 to 1975, mostly due to human interventions, and the large widening that occurred from 1975 to 2003, mostly due to the 2000 severe flood (after Pellegrini & *alii*, 2008).

per plain. This was favoured by a process of incision of the river bed. The only data available on this process refer to a field survey carried out in the 1970s along a 25 km long reach of the Orco River (Govi, 1976). Aerial photograph analysis and topographic field measurements provided some assessments of the different river bed levels between the 1945 and the 1975 channel positions. The data acquired in 20 selected sites suggested that the major phase of incision had occurred over the 1961-1975 period with a river bed deepening of 1÷2 m on average in 14 sites and a single local maximum of 3.5 m.

Recent channel changes

Channel-width changes

Thanks to the restrictive rules issued by local and national Authorities (Bianco, 1997) the in-channel sediment mining has been almost stopped since the beginning of the 1990s. In this new situation of gravel and sand availability the 1993 flood and above all the 2000 flood heavily modified the river bed geometry leading to an opposite trend with regard to the previous channel narrowing (Turitto & *alii*, 2008).

It has to be pointed out that the 2000 flood has been the maximum recorded since 1920 (fig. 4). The ARPAP (2003, p. 55) assigned it a return period of 80 years. During this flood severe bank erosion processes took place and channel avulsions dissected the older or new islands from the floodplain, inducing a widening of the total channel (see the 1975 and 2003 channel configurations in fig. 3). On the whole 25 km long reach the channel widening reached +133% on average compared with the 1989 width (fig. 2).

Bed-level changes

Remarkable vertical adjustments even occurred in the river bed, caused by severe processes of sediment erosion and deposition. They have been deduced by the stereoscopic analysis of aerial photographs, but no topographic data of these processes are available.

Only very occasional assessments of bed level changes were made by a Technical Office along a 2 km reach of the Orco River near the town of Salassa (Studio Associato Ser.P.I., 2005). The Technical Office compared the channel geometry drawn before and after the 2000 flood at 19 cross-sections. The comparison showed a severe move-

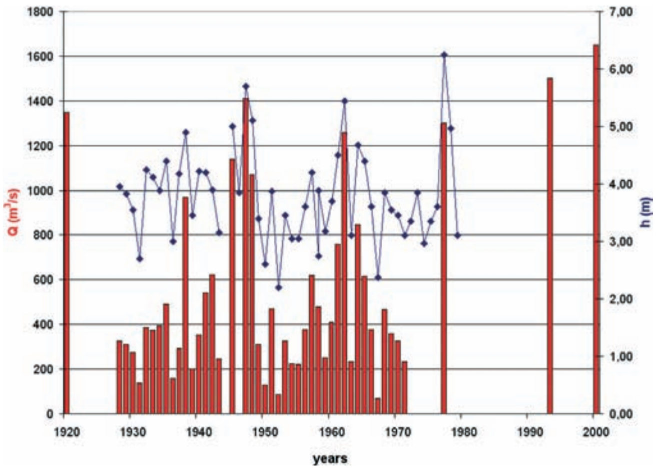

FIG. 4 - Historical trends of maximum annual level (h, in blue) and/or discharge (Q, in red) of the Orco River over the investigated period. No severe floods occurred in the years when data were not available.

ment and displacement of fluvial sediments (above all coming from bank erosion), inducing in some cross-sections a prevalence of deposition areas and in other ones a prevalence of erosion areas (see Turitto & *alii*, 2008, fig. 6E). On the whole in these 19 cross-sections the addition of erosion areas was roughly equal to the one of deposition areas.

After the 2000 flood further morphological investigations were carried out comparing three DTMs corresponding to the 2003, 2004 and 2006 fluvial configurations of the last 40 km of the Orco River (Lollino & *alii*, 2007). The three DTMs were generated by the same survey procedures (airborne LiDAR acquisition) and also in the analogous very low river stage so as to draw and compare the largest extent of the river bed in dry conditions.

Investigations provided a volumetric assessment of erosion and deposition processes which had occurred in the emerged part of the channel between the above-mentioned surveys. It must be pointed out that no significant floods occurred during the investigated period, but widespread river regulation works were carried out after the 2000 flood, altering natural river dynamics.

Significant morphological variations due to the erosion/deposition processes were detected between 2003 and 2004 on 23% of the dry channel. The alternation of prevalent deposition sites with prevalent erosion sites led on the whole to a positive, although low, balance of sediment volumes (+39 000 m^3, as a difference between 253 000 m^3 of deposition and 214 000 m^3 of erosion), despite an artificial removal of about 100 000 m^3. On the contrary a negative balance of sediment volumes came out from 2004 to 2006 (–150 000 m^3) on 12% of the dry channel. In this case eroded volumes (308 000 m^3), however, prevailed in the upper half of the river course, whereas deposited volumes (158 000 m^3) prevailed in the lower half.

Where and when a positive balance was detected, it may be interpreted as a small rise of the mean level of the river bed (aggradation), although most probably only local and perhaps only temporary.

Therefore in the contest of the historical and more recent channel changes, there are many quantitative data on planimetrical adjustments, but very few, and often only local, data on altimetrical adjustments with severe spatial and temporal gaps.

As pointed out in the introduction, the DTMs of the Orco River ensure two important prerequisites: 1) the coverage of the present channel and its surrounding floodplain with the relic and dated fluvial forms; 2) the very high density and accuracy of the topographic point data. These important conditions suggested a DTM use to test a method to fill in part the temporal gap on vertical channel changes. Using the 2003-DTM we attempted an assessment of the river bed incision occurred over the last 100 years in a small selected reach.

Selected reach

A 3 500 m fluvial reach was selected in the middle course of the Orco River (see its location in fig. 1) where historical information and landform features allow to reconstruct channel adjustments in space and time.

In figure 5 there are some cartographic and photographic documents showing the channel planform changes. These changes are due to both artificial constraints and natural causes. In the first case, the construction of two bridges (the Rivarolo bridge, built in the upper reach in 1850, and the Feletto bridge, built in the lower reach in 1935) led to a remarkable channel constraint (tab. 2). These interventions heavily reduced the channel width with long earthen approaches and spans too small for the natural channel width (Turitto & Audisio, 2008). They also produced the flow concentration in a prevalent channel shifted against the right bank (15÷20 m high and incised in an old alluvial fan) preventing a further free mobility of the river towards this side. Whereas on the left side the river was free and frequently able to flow onto the floodplain, along the old river branches, often threatening, damaging and destroying the bridge approaches and the bridges, too (the Rivarolo bridge was knocked down in 1993, the Feletto bridge in 2000). The water concentration in the prevalent channel also produced a vertical erosion and led to a river bed deepening down to the local incision of lacustrine deposits previously buried by fluvial deposits (fig. 6). This process was further increased by the excessive dredging of gravel and sand carried out in the second half of the last century.

A reverse trend, towards a widening of the total channel, was due to natural causes as the severe floods occurred over the last century and measured at the Pont Canavese gauging station (fig. 4) (Turitto & *alii*, 2008): the October 1945 flood (1 140 m^3/s), the September 1947 one (1 410 m^3/s) and the September 1948 one (1 070 m^3/s) which produced the planform changes occurred between 1945 and 1957 (B and C in fig. 5); the September 1993 flood (1 500 m^3/s) and the October 2 000 one (1 650 m^3/s) which

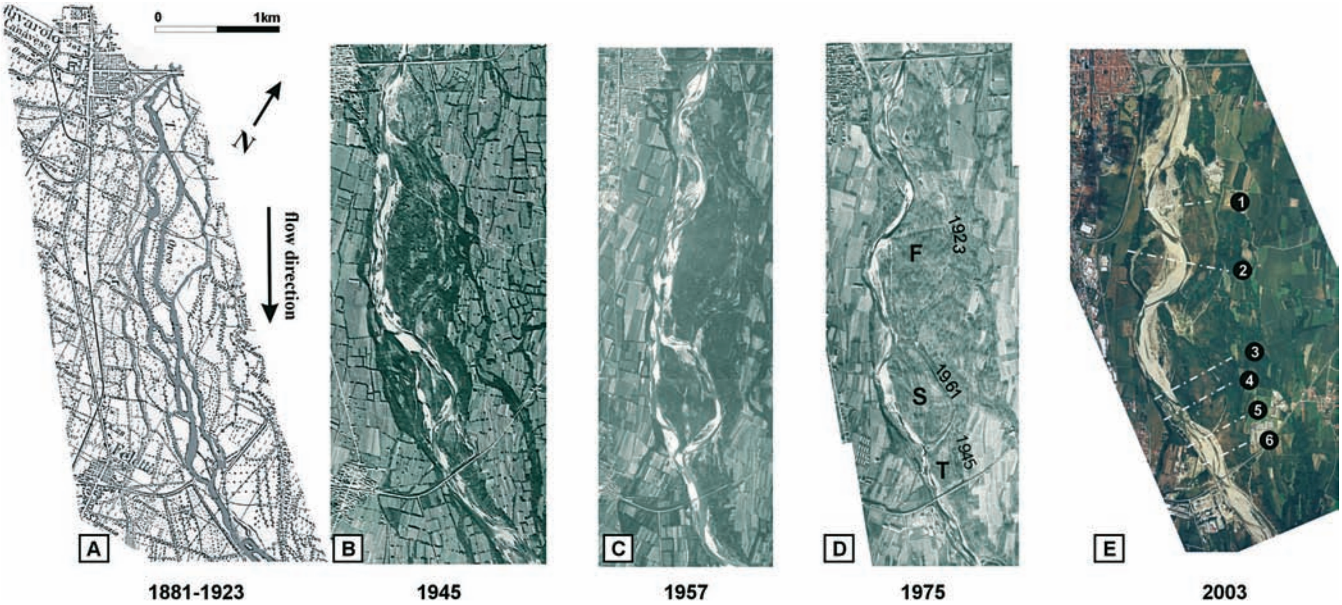

FIG. 5 - The Orco River selected reach at various dates showing progressive morphological changes. Channel position and configuration: A) in 1923 (IGMI map), the same on 1881 IGMI map; B) in 1945 (IGMI aerial photograph); C) in 1957 (CNR-IRPI aerial photograph), similar in 1954 and 1961; D) in 1975 (CNR-IRPI aerial photograph), similar in 1989, with older and dated channel positions; F, S and T show the first, the second and the third sub-reaches; E) in 2003 (Provincia di Torino aerial photograph), similar in 2000, with the traces of the six cross-sections drawn out from the 2003-DTM.

TABLE 2 - Rivarolo and Feletto bridges: features of crossing sites and dimensions of bridge structures (after Turitto & Audisio, 2008)

bridge	slope of the fluvial reach (%)	bed material G gravels C cobbles B small boulders	width of the flood plain (m)	width of the channel at time of building (m)	length of the left bridge approach (m)	length of the bridge (m)	length of the right bridge approach (m)
Rivarolo bridge built in 1850	~1	CGB	970	500	600	70	300
Feletto bridge built in 1935	~ 0.6	CG	370	370	240	130	–

strongly modified the previous morphology towards a large channel widening (D and E in fig. 5).

All aerial photographs of this selected reach clearly show the old channel positions on the surrounding river floodplain. The 1881 position was occupied in the upper reach at least until 1923, whereas in most of the lower reach the 1881 position was occupied until 1961 and in its remainig part till 1945 (fig. 5 D). The aim of our testing approach is to find out about the different mean level of the river bed between the recent and these former channel positions.

FIG. 6 - The Orco River 1.5 km upstream of the Feletto bridge in January 2007 (downstream to the left). Since the beginning of the 1980s the vertical erosion has incised the lacustrine deposits previously buried by fluvial deposits.

METHODS

LiDAR technology

The use of LiDAR technology began in the late 1990s to generate Digital Terrain Models (DTMs) of broad land areas through the use of airborne sensors (Naesset, 1997; Baltsavias, 1999). In environmental studies, laser scanners are normally employed to create Digital Elevation Models (DEMs) from which, through appropriate filter algorithms, high-resolution DTMs can be generated to understand landform changes induced by exogenous modelling processes (Ackermann, 1996; Axelsson, 1999).

The two main types of data obtained with laser scanners can be divided into: 1) a «pointcloud» from which a Digital Surface Model (DSM) and a DTM can be created; 2) a photographic image of the scanned area taken with a digital camera (Murakami & *alii*, 1999). By merging the laser data with the photographic image, a digital orthophotograph is also generated. This type of photograph is essential during the phase of morphological data analysis (Beraldin & *alii*, 2000; McIntosh & Krupnik, 2002). This photographic image, in fact, allows to recognize on the ground what laser data reflect and so it will be easier to exclude areas where data are not reliable.

With this type of instrumentation we were able to acquire and classify numerous points to produce a discrete and continuous morphological representation of the study area. The particular feature of this system is that it can acquire and characterize, depending on the properties of the reflected light wave (normally 3 wavelengths), the type of objects or ground features the light has bounced back from, allowing a classification of the target attributes and an application of filter algorithms to remove unwanted objects (Brovelli & Cannata, 2004; Kraus & Pfeifer, 1998).

The time the reflected light takes to travel out to and bounce back from a target (emission-reflection-reception) determines the distance between the mirror and the ground reflection point (Hofton & Blair, 2002). At the same time of the recording phases, Global Positioning System (GPS) ground stations were set up around the study area enabling us to determine the trajectory of the aircraft flight path, through kinematic differential positioning. Added to the GPS trajectory there is a system of orientation and accelerometric data coming from the Inertial Measurement Unit (IMU) generated by the sensors on the aircraft.

LiDAR acquisition

To obtain a set of input data for understanding the 2003 morphological configuration of the Orco River (Lollino & *alii*, 2007), an Optech ALTM-3033 airborne LiDAR sensor was used. It was equipped with a ROLLEI H20 digital semimetric camera and mounted on an AS350 Ecureil helicopter. This survey was taken at a middle flying height of 750 m above ground level and provided the orthophotographic and laser coverage of the river course and its surrounding floodplain with a point density of 2 pts/m^2.

Accuracy

At this flying height, the average altimetric accuracy, calculated on the WGS84 ellipsoid, is, in theory, approximately 15 cm, while the planimetric (E-N) accuracy, calculated on the UTM plane projection expressed on the WGS84 ellipsoid, is generally equal to around 40 cm (1/2000*H flight [m]). This accuracy depends anyway on factors like the geometric distribution and number of GPS satellites, Diluition of Precision (DOP) values, etc. In this regard the ground resolution of the orthophotographic product is nominally equal to 18 cm/pixel but it was actually produced at 40 cm/pixel with an absolute positioning accuracy of around 50 cm.

It has to be pointed out that the reconstruction of the submerged area of the river bed is not possible as the LiDAR systems cannot penetrate water. Therefore the survey was taken under very low-water conditions (on 6th August 2003 with 1.17 m^3/s at S. Benigno gauging station, 846 km^2 of drainage area) to cover a large portion of the channel usually submerged by water.

Reliability tests and errors

After having successfully classified the entire pointcloud according to the ground, low/medium/high vegetation and building algorithms, several reliability tests were carried out to verify the accuracy level of the laser survey. In particular, a series of geodetic high-precision ground surveys was planned to equip the covered area with a benchmark reference network (27 GPS benchmarks referred to the Italian Geodetic Reference Frame). These benchmarks were used either to rototraslate the conventional optic and GPS static-real time control measurements or to adjust the kinematic trajectory of the aircraft during survey operations.

We, then, verified the accuracy in the altimetric ellipsoidical direction, as an estimation of altimetric river bed changes was our first objective, and the accuracy of the orthophotograph absolute orientation. These tests were performed measuring approximately one hundred GPS points within 1 cm accuracy level to check: 1) the altimetric reliability over unaltered flat surfaces, like parking areas (at the intersection of the white lines); 2) the external orientation of the orthophotograph. The reference frame adopted for both control operations and all generated products was the WGS84 in UTM (fuse 32 North) plane projection, according with the Regional Technical Map on a 1:10 000 scale. Moreover, some topographic cross-sections, measured with optic instruments and oriented over two or more GPS high-precision benchmarks, were compared with the cross-sections coming from the laser pointcloud on the same baseline to verify their matching. The result shows that the altimetric difference is less than 10 cm (always calculated on the WGS84 ellipsoidical height) and the accuracy level of the orthophotograph external orientation is approximately 40 cm in N-E direction.

Cross-sections of the selected reach

From the 2003 DTM and orthophotographic coverage of the Orco River, the selected reach was drawn out and the six cross-sections, useful to test our method, were laid out (fig. 7). Every cross-section was drawn perpendicularly to the present fluvial axis and lengthened beyond the left bank enough to cross the remaining portion of the older channel positions still well preserved on the floodplain.

The methodology used to extract the river cross-sections, validated as explained before, started by a high-density DTM creation with a low interpolation (natural neighbourhood) thanks to the high density of ground point dataset (2 pts/m^2). The vector was positioned directly upon the orthophotograph and the DTM and used to intercept the DTM surface, extracting its numerical information (East, North and Height values) with 1 m steps.

The datasets of each cross-section were processed to compare numerically and graphically the altimetric bed levels in different times.

Present and older bed levels

On each cross-section the limits of the present and the older river beds are identified by merging the photographic interpretation and DTM data (fig. 8). Afterwards the mean level of every river bed, the present one (2003) and the old ones (1923, 1945 and 1961), was extracted from the processed data of the six cross-sections (see red lines in fig. 8). This operation allowed to average the more stressed unevenness of every river bed.

Assessment of channel incision

For each cross-section the channel incision was assessed as a difference between the old and the present mean levels of the river bed. We supposed that when the 1923 channel was occupied by water (before its abandonment after 1945 and 1961, depending on different sites) the mean level of its bed could not be lower than it was in 1945 and 1961, but higher at most. Since the incision we measured from the 1945 and 1961 positions can be reasonably referred to the original 1923 position, at most it may in reality have been bigger.

It has to be pointed out that no significant depth of sediments filled the abandoned channels at the crossed sites. Sediments and colluvial deposits just filled the gaps among the cobbles (fig. 9a and 9b). Moreover, in some cases old channels can still be occupied by flowing water during heavy rainfall (fig. 9c).

RESULTS

The analysis of historical maps and aerial photographs allowed to identify along a 3 500 m selected reach of the Orco River three different sub-reaches (F, S and T in fig. 5 D) where the 1881/1923 channel position was naturally or artificially abandoned by the river in three different periods of the last century: after 1923 in the first 2 000 m (downstream of the Rivarolo bridge), after 1945 in the last 500 m (immediately upstream of the Feletto bridge) and after 1961 in the remaining middle 1 000 m.

As previously pointed out, from the 2003-DTM six cross-sections were drawn (two for each sub-reach) so as to cross the present position of the river channel and the older ones well preserved on the surrounding floodplain and not encroached by sediment extraction (see the traces of the six cross-sections in fig. 5 E and in fig. 7).

And then, thanks to the altimetric data provided by the cross-sections (fig. 8), the difference from the old to the present mean levels of the river bed was measured. In table 3 these altimetric data were associated with the channel widths and their percentages of change (increases/decreases) at various dates.

Despite the margin of error in the above-mentioned planimetric and altimetric measurements, morphological

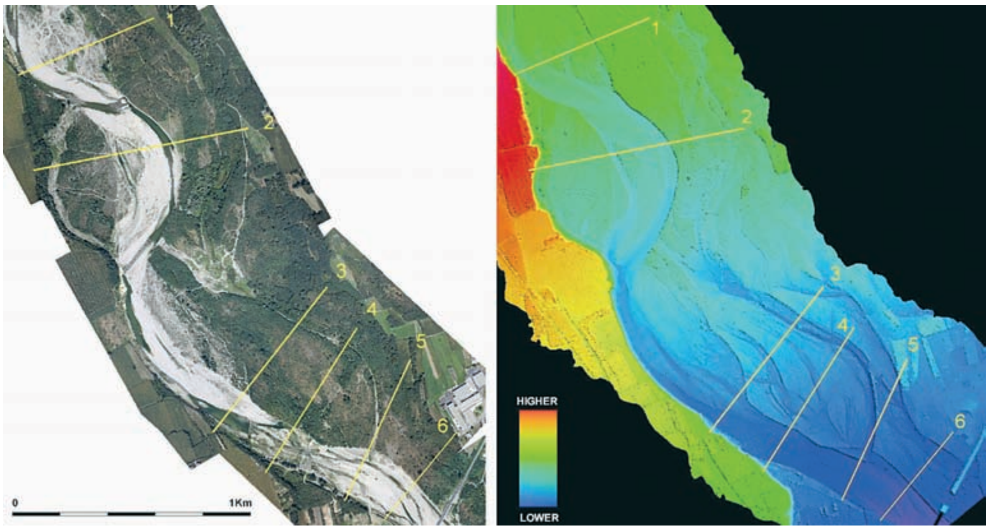

FIG. 7 - The 2003 orthophotograph and DTM of the selected reach over which the traces of the six cross-sections are marked.

FIG. 8 - The six cross-sections, drawn out from the 2003-DTM, are numbered 1 to 6 from upstream to downstream. The positions of the present channel (2003) and of the remaining portions of the older ones (occupied until 1923, 1945 and 1961) are given. The red lines show the mean level of the river bed in different years.

changes are remarkable and significant. The results suggest the following considerations.

First sub-reach (cross-sections 1 and 2)

Along the first 2 000 m of the selected reach (F in fig. 5 D) the left ramifications occupied by the river in 1881 and up to 1923 were abandoned before 1945 (see A and B in fig. 5). This morphological simplification led to a significant reduction of the total channel width down to 60÷70% (see cross-sections 1 and 2 in tab. 3), more than twice as much the reduction of the mean width of the channel coming from the six cross-sections (about 30%, see last line in tab. 3). A bed deepening may also have occurred over this period in these first 2 000 m, but today nobody can quantify its extent.

After the severe floods of the second half of the 1940s a channel widening occurred (+18% and +48% at cross-sections 1 and 2, respectively, from 1945 to 1961), whereas a narrowing occurred after 1961 up to 1989. Over the whole 1923-1989 period the river underwent a severe narrowing (–70÷80%). This was higher than the mean width

TABLE 3 - Morphological channel changes in the Orco River selected reach (3.5 km long) between Rivarolo and Feletto bridges over the 1881/1923-2003 period. Channel widths, including fluvial islands, are drawn out from historical maps and aerial photographs. The width increases/decreases (± %) are also given compared to the previous values (between brackets the reference years), as *stable* the changes <10%. Mean bed levels (above local datum) and bed incisions are drawn out from cross-section data

cross-sections	**1881-1923** *same channel configuration*		**1945**		**1954-1957-1961** *similar channel configuration*		**1975-1989** *similar channel configuration*	**2003**	
	channel width in 1923 (m)	**mean bed level** (m a.l.d.)	*channel width (m)*	**mean bed level** (m a.l.d.)	*channel width in 1961 (m)*	**mean bed level** (m a.l.d.)	*channel width in 1989 (m)*	*channel width (m)*	**mean bed level** (m a.l.d.)
1	*465*	**327.20**	*178 –62%*		*217 +18% (1945) –53% (1923)*		*121 –44% (1961) –74% (1923)*	*311 +157% (1989) –33% (1923)*	**324.50**
					bed incision 2.7 m (0.03 m/yr)				
2	*543*	**323.30**	*139 –74%*		*206 +48% (1945) –62% (1923)*		*97 –53% (1961) –82% (1923)*	*224 +131% (1989) –59% (1923)*	**321.00**
					bed incision 2.3 m (0.03 m/yr)				
3	*219*		*245 +12%*		*513 +109% (1945) +134% (1923)*	**316.60**	*127 –75% (1961) –42% (1923)*	*189 +49% (1989) –14% (1923)*	**314.60**
				?			**bed incision 2.0 m (0.05 m/yr)**		
4	*196*		*321 +64%*		*526 +64% (1945) +168% (1923)*	**315.20**	*137 –74% (1961) –30% (1923)*	*149 stable (1989) –24% (1923)*	**312.50**
				?			**bed incision 2.7 m (0.06 m/yr)**		
5	*268*		*269 stable*	**313.80**	*123 –54% (1945) –54% (1923)*		*128 stable (1961) –52% (1923)*	*158 +23% (1989) –41% (1923)*	**310.10**
		?				**bed incision 3.7 m (0.06 m/yr)**			
6	*342*		*314 stable*	**311.70**	*89 –72% (1945) –74% (1923)*		*117 +31% (1961) –66% (1923)*	*166 +42% (1989) –52% (1923)*	**308.60**
		?				**bed incision 3.1 m (0.05 m/yr)**			
	mean width 339		*mean width 244 –28%*		*mean width 279 +14% (1945) –18% (1923)*		*mean width 121 –57% (1961) –64% (1923)*	*mean width 199 +65% (1989) –41% (1923)*	

coming from the six cross-sections over the same period (–64%).

A large part of the width lost in the previous period was recovered during the 2000 flood. The increase was more than 150% at cross-section 1 and 130% at cross-section 2 (referred to the 1989 width). The new width, however, did not reach the 1923 one.

In these different and alternate events the mean bed level deepened at least 2.7 m at cross-section 1 and 2.3 m at cross-section 2.

Second sub-reach (cross-sections 3 and 4)

Along the following 1 000 m (S in fig. 5 D) the channel width, contrary to what occurred in the first sub-reach, underwent a widening between 1923 and 1945 with +12% and +64% at cross-sections 3 and 4, respectively (tab. 3). Afterwards, the channel configuration was hardly modified during the floods in the second half of the 1940s by the activation of two main ramifications. Between these ramifications a ground portion with secondary channels and vegetated bars progressively became an island rarely submerged by water in the following years (see B and C in fig. 5). This process induced a widening of the total channel (inclusive of the new island) at both cross-section 3 (+100% with regard to the 1945 width and +130% to the 1923 one) and cross-section 4 (+60% with regard to the 1945 width and even +160% to the 1923 one).

The following abandonment of the left ramification, occurred between 1961 and 1963, led to the island joining the floodplain and, then, to the channel narrowing (see C and D in fig. 5). In 1989 the width reached –75% of the 1961 one. The 2000 flood did not significantly modify the channel width at cross-section 4, whereas an enlargement occurred at cross-section 3 (+50%).

In this sub-reach the rate of bed incision was 2.0 m at cross-section 3 and 2.7 m at cross-section 4.

FIG. 9 -The present appearance of the abandoned channels: A) the channel occupied until 1961 and intercepted by cross-section 4 (photograph taken in September 2007); B) the one occupied up to 1945 and intercepted by cross-section 6 (photograph taken in April 2009); C) the one occupied up to 1923 and intercepted by cross-section 2 (photograph taken in April 2009, after heavy rainfall).

Third sub-reach (cross-sections 5 and 6)

In the last 500 m of the selected reach, immediately upstream of the Feletto bridge (T in fig. 5 D), the 1923 position was artificially closed off after 1945 to prevent recurrent threats to the bridge (see B and C in fig. 5).

Over this 22-year period the channel width remained around 200÷300 m, but significantly decreased between 1945 and 1961, reaching –50÷70% (see cross-sections 5 and 6 in tab. 3). This narrowing occurred despite the 1940s floods which enlarged the previous sub-reaches. Afterwards, and up to 1989, the channel width was stable at cross-section 5, whereas it increased to a moderate extent at cross-section 6 (+31%), when in the other sub-reaches a more or less noticeable decrease occurred. The following situation (after the 2000 flood) documents a further increase (+20÷40%) when the previous sub-reaches showed a stability or a low instability (the second) and a very large widening (the first).

In this last sub-reach the bed incision reached more than 3 m. At cross-section 5 (fig. 8) we can also see the different lowering which occurred from 1945 to 1961 (2.4 m) and from 1961 to 2003 (1.2 m).

Spatial and temporal morphological evolution of the overall selected reach

The analysis of the previously described planimetric and altimetric adjustments of the channel has furnished some information which can be summarized as follows.

– In the 3.5 km selected reach the evolutionary trend of the total channel width between 1923 and 2003 (considered as a mean width of the total channel coming from the six cross-sections, see the last line in tab. 3) well enough reflects the one measured in the 2005 research and referred to the 25 km river course (fig. 2).
– Every single sub-reach (2 000 m, 1 000 m and 500 m long, respectively from upstream to downstream) follows, however, its peculiar history in morphological changes: at times a narrowing comes out in a sub-reach when in the other ones a stability or a widening occurs and vice versa (see channel widths in tab. 3).
– In 1989 all sub-reaches showed a small channel width, varying from a minimum of 97 m at cross-section 2 to a maximum of 137 m at cross-section 4. The mean width coming from the six cross-sections is the smallest in the investigated 80-year period, corresponding to –64% of the 1923 width, which reached few hundred metres in almost every cross-section.
– The 2000 flood produced a large channel widening, the mean width from the six cross-sections in 2003 (199 m) being +65% referred to the 1989 one (121 m). It was very significant, however, only in the first sub-reach (+130÷150%) where the 1923 channel width was the largest (400÷500 m) and the following narrowing very intense (–70÷80% from 1923 to 1989).
– Despite the different morphological evolution of each sub-reach, the river bed deepened down to 2÷3 m and

more between 1923 and 2003 along the overall selected reach, even if the 1923 position was abandoned at different times.

– A good part of this total deepening occurred after 1961 (2.0 m and 2.7 m at cross-sections 3 and 4, respectively, in tab. 3) during the major phase of the channel narrowing (fig. 2). Whereas at cross-section 5 the main phase of incision was measured from 1945 to 1961 (2.4 m out of 3.70 m from 1945 to 2003), corresponding to the decades following the Feletto bridge construction (built in 1935).
– The data on the above-described channel incision (2÷3 m on average) differ slightly from the previous results of the 1975 research (1÷2 m on average) through merging aerial photograph interpretation and topographic field measurements (Govi, 1976). In addition to the different lengths of the investigated reaches (3.5 km of our study out of 25 km of the 1975 study), the 1975 measures were referred to a shorter and older period (30 years from 1945 to 1975). Despite these differences, the comparison could confirm that the incision processes continued even after the 1970s.

DISCUSSION

The primary goal of our research was to test a method to investigate bed level changes occurred along a river reach and on a large time scale when other data are not available (e.g. for lack of previous topographic or quantitative data) or other techniques require more time (e.g. acquisition and comparison of aerial photogrammetries).

The suggested method is based on a combination of different data sources and procedures: a) published and unpublished information; b) historical map interpretation; c) stereoscopic analysis of aerial photographs; d) GIS application; e) LiDAR technique; f) DTM use. They were combined to acquire and process quantitative data on the occurred bed level incision at a selected river reach.

Analogous and helpful information can also be provided by river cross-sections coming from topographic field survey or aerial photogrammetry (e.g. Surian & *alii*, 2009b). In these cases, however, the number and the sites of the cross-sections were or must be established previously. Whereas, thanks to the very high density of the point data provided by LiDAR techniques, our method allows to quickly acquire the topographic data at an about unlimited number of cross-sections and at any useful and significant site.

The method was applied on a 3 500 m fluvial reach located in the middle plain of the Orco River and divided into three sub-reaches (2 000, 1 000 and 500 m long) with different changes in channel widths at the same time. These changes were due to both natural and human causes.

Despite the different morphological evolution of each of the three sub-reaches, the study showed that, over the investigated 80-year period (1923-2003), the river bed had undergone an incision of 2.7 m on average along the overall selected reach, with a minimum of 2 m and a maximum of 3.7 m (tab. 3).

Even if we cannot exclude that the process of channel incision may have started for natural causes, without doubt the heavy constraints induced by the construction of two bridges, in 1850 and in 1935 (tab. 2), and by their later protections favoured the narrowing and the consequent deepening of the river channel. These processes occurred not only at the crossing sites but also along the whole channel between the two bridges. It must be pointed out, however, that far from the Rivarolo and Feletto bridges the incision was smallest (about 2 m at cross-sections 2 and 3) and upstream of the Feletto bridge biggest (over 3 m at cross-sections 5 and 6). In this last site a traverse of water diversion was built across the river in the 1950s, but it was repeatedly destroyed by undermining processes until the end of the 1970s and never built again.

At last, far from the bridges the major rate of incision (2 m and more out of over 3 m) seems to have come out after 1961 (see cross-sections 3 and 4), in the same period of the more intense channel narrowing and when an uncontrolled in-channel sediment dredging took place.

At present we cannot know if the extent of the bed incision we found out at the selected reach had involved the whole channel of the Orco River in the plain. Moreover, we cannot know if the incision process had continued up to the occurrence of the severe 2000 flood or if it had already stopped, or reduced, after 1989 (as a result of the more restrictive provisions about gravel and sand mining within the channel). Therefore we cannot even know if the channel widening we found after 1989 had even been accompanied by a rise of the mean bed level (aggradation). This last circumstance could suggest that the rate of incision we assessed between 1961 and 2003 may actually have been the result of a first major phase of incision followed by a short phase of sedimentation. In this case the real incision occurred until 1989 may have been bigger than the one measured until 2003.

On the other hand, the comparison of the 2003, 2004 and 2006 DTMs, demonstrates that a bed level rise took place somewhere along the Orco River after the severe floods of the end of the last century and in a period of ordinary river stages. We can reasonably suppose that this process had naturally started since the end of the 1980s, at the same time of the start of the channel widening. It corresponds to the above-mentioned period with a higher sediment availability, following the reduction of sand and gravel mining. Unfortunately high magnitude floods took place soon after and prevented us from knowing the morphological channel adjustments which would have occurred without these severe floods.

Other tests on other Orco River reaches (with well preserved old channel positions and, if possible, without excessive human constraints and heavy flood effects) could perhaps give some answers to all these questions.

If our supposition, about a probable stop of the prevalent phase of incision since the end of the 1980s, is confirmed, we may infer that the Orco River underwent (although only somewhere) similar bed level changes found in several investigated rivers of Northern and Central Italy (Surian & *alii*, 2009a). In fact, many of these Italian rivers incised their channels above all between the 1960s and 1980s at the same time of their narrowing. At a later phase they raised (or stabilized) their bed levels after the 1980s at the same time of their widening (from the 1980s/1990s to 2003/2007, depending on different cases). The rate of their widening, however, was much lower than the Orco one.

Such an intense channel widening of the Orco River (+133% on average along a 25 km reach from 1989 to 2003) may have been larger than all the other investigated Italian rivers (mainly ranging between 9% to 59% over about the same period, see Surian & *alii*, 2009a) for three main reasons:

a) a smaller human impact with still a larger space for a free planimetric mobility of the channel (see in fig. 5 the expanse of the riparian wood in the selected reach, typical of the whole river course in the plain);
b) a moderate incision of the river bed (2÷3 m on average compared with a prevalent range of 4÷5 m in the other investigated rivers and up to 8÷10 m in some of their middle or lower sub-reaches);
c) the occurrence of a very large flood in 2000 (the highest of the Orco River in an 80-year recorded period), which took place only in another of the 12 investigated rivers (i.e. in the Stura di Lanzo River flowing near the Orco River).

CONCLUDING REMARKS

The testing approach presented in this work allowed a quantification of the occurred incision in a selected reach of the Orco River over the last century. The technique employed to assess the incision (LiDAR acquisition and DTM generation) entailed a certain margin of error in the measures. This margin of error, however, is very low comparing with the extent of the measured incision (± 10 cm of error out of 2÷3 m and more of incision).

Despite the uncertainty of the exact chronological reconstruction of the occurred incision, its long-term quantification, however, provides an important new step in understanding the morphological evolution of the river.

The study case demonstrates the further potential of LiDAR techniques when combined with the past and the more recent history of the river (coming from bibliographic data, historical map information and aerial photograph interpretation). It represents a new investigation path towards the past, when conventional applications are at present focused on monitoring the future changes starting from a first survey.

Our methodology even allows to acquire many and sufficiently accurate quantitative data of channel morphological adjustments on a very large time scale (long-term investigation back to a century ago). That is possible only if older and datable channel forms are still well preserved on the ground surface and if a certain margin of error can be acceptable in quantifying changes.

The attempted method can prove a useful tool for the control of old altimetric variations of channel forms above all when no comparison of previous topographic data is possible and even when no topographic field surveys are possible due to, for example, local accessibility problems. Moreover, measures by LiDAR techniques are certainly more accurate by comparison, for example, with photogrammetry.

In the measurements of the bed level of an abandoned channel, however, one must ensure that the original morphology has not changed in time through natural phenomena or human activities. In particular, one must verify the presence of sediments filling the old abandoned channel during later river overflowings or by land-use practices. If by field survey the presence of these sediments comes out, their depth must be assessed and considered in the measurements, comparing it with the margin of error in the measures.

The research pointed out that to understand the present dynamics of a river and foresee the evolutionary trend of its horizontal and vertical adjustments, a continuous monitoring of channel morphologies, using the airborne LiDAR techniques, is needed and hoped for. Information about probable future channel changes, however, cannot be separated from, and must be supported by, the reconstruction of the past channel changes and their main natural or artificial causes.

Old, recent and future information on planimetric and altimetric channel changes will be able to provide the basis to understand: (1) the processes of sediment erosion, transport and deposition, (2) the consequent channel adjustments in space and time, and (3) the positive or negative implications in physical, ecological and human environments. Only their knowledge, supported by specific hydrologic and hydraulic studies, can suggest the opportunity or the methods to go on in the exploitation of river resources (water and sediments), modifying natural discharge and sediment load which are the main variables driving fluvial dynamics and patterns.

REFERENCES

ACKERMANN F. (1996) - *Airborne laser scanning for elevation model*. GIM Geomatics Info Magazine, 10, 24-25.

ARPAP (AGENZIA REGIONALE PER LA PROTEZIONE AMBIENTALE DEL PIEMONTE) (2003) - *Eventi alluvionali in Piemonte: 13-16 Ottobre 2000*. ARPA Piemonte, Torino, 327 pp.

AXELSSON P. (1999) - *Processing of laser scanner data-algorithms and applications*. ISPRS Journal of Photogrammetry & Remote Sensing, 54 (2-3), 138-147.

BALTSAVIAS E.P. (1999) - *A comparison between photogrammetry and laser scanning*. ISPRS Journal of Photogrammetry and Remote Sensing, 54 (2-3), 83-94.

BERALDIN J.A., BLAIS F., BOULANGER P., COURNOYER L., DOMEY J., EL-HAKIM S.F., GODIN G., RIOUX M. & TAYLOR J. (2000) - *Real world modelling through high resolution digital 3D imaging of objects and structures*. ISPRS Journal of Photogrammetry & Remote Sensing, 55 (4), 230-250.

BEZOARI G., BRAGA G., GERVASONI S., LARCAN E. & PAOLETTI A. (1984) - *Effetto dell'estrazione di inerti sull'evoluzione dell'alveo del fiume Trebbia*. 2° Convegno di Idraulica Padana, Parma 15-16 giugno 1984, Magistrato per il Po, Parma, 163-182.

BIANCO G. (1997) - *Attività estrattiva nelle fasce di pertinenza fluviale*. Atti della Giornata di Studio su «Aspetti tecnici e normativi nell'estrazione di inerti e pietre calcaree per uso industriale», Torino 13 Novembre 1997, Politecnico di Torino, Associazione Georisorse e Ambiente, Torino, 61-67.

BIANCO G., GASCA R. & BERTA A.M. (2005) - *Rapporto sullo stato di avanzamento degli studi e dei risultati raggiunti nel primo anno*. Contratto di ricerca per lo svolgimento di attività relativa al monitoraggio e manutenzione del Fiume Orco nel tratto Pont Canavese-Po. Regione Piemonte-Direzione Difesa del Suolo e Politecnico di Torino-Dipartimento di Idraulica, Trasporti ed Infrastrutture Civili, Unpublished Report, 148 pp.

BORGATTI L. & SOLDATI M. (Eds.) (2005) - *Geomorphological Hazard and Human Impact in Mountain Environments.* Geomorphology, Special Issue, 66 (1-4), 383 pp.

BRAVARD J.P., KONDOLF G.M. & PIÉGAY H. (1999) - *Environmental and societal effects of channel incision and remedial strategies*. In: Darby S.E. & Simon A. (Eds.) «Incised River Channels: Processes, Forms, Engineering and Management», Wiley, Chichester, 303-341.

BROCCOLATO M., MARTELLI D.C.G. & TAMBURINI A. (2006) - *Il rilievo geomeccanico di pareti rocciose instabili difficilmente accessibili mediante impiego di laser scanner terrestre. Applicazione al caso di Ozein (Valle di Cogne, Aosta)*. Geoingegneria Ambientale e Mineraria (GEAM), 43 (4), 39-46.

BROVELLI M.A. & CANNATA M. (2004) - *Digital terrain model reconstruction in urban areas from airborne laser scanning data: the method and an example for Pavia (northern Italy)*. Computers & Geosciences, 30 (4), 325-331.

CANUTI P., CENCETTI C., CONVERSINI P., RINALDI M. & TACCONI P. (1992) - *Dinamica fluviale recente in alcuni tratti dei Fiumi Arno e Tevere*. Atti del Convegno «Fenomeni di erosione e alluvionamenti degli alvei fluviali», Ancona 14-15 Ottobre 1991, Università degli Studi di Ancona, Ancona, 21-35.

CASTIGLIONI G.B. & PELLEGRINI G.B. (1981) - *Geomorfologia dell'alveo del Brenta nella pianura tra Bassano e Padova*. In: Zunica M. (Ed.) «Il territorio della Brenta», Amministrazione Provinciale di Padova e Università di Padova, Padova, 12-32.

CENCETTI C. & FREDDUZZI A. (2008) - *Analisi attraverso metodologia GIS delle variazioni dei caratteri morfologico-sedimentari nella bassa valle del F. Sinni (Basilicata)*. Il Quaternario, 21 (1B), 147-160.

CHARLTON M.E., LARGE A.R.G. & FULLER I.C. (2003) - *Application of airborne LiDAR in river environments: the River Coquet, Northumberland, UK*. Earth Surface Processes and Landforms, 28, 299-306.

CHEN R.F., CHANG K.J., ANGELIER J., CHAN Y.C., DEFFONTAINES B., LEE C.T. & LIN M.L. (2006) - *Topographical changes revealed by high-resolution airborne LiDAR data: The 1999 Tsaoling landslide induced by Chi-Chi earthquake*. Engineering Geology, 88, 160-172.

DELINE P., DIOLAIUTI G., KIRKBRIDE M.P., MORTARA G., PAVAN M., SMIRAGLIA C. & TAMBURINI A. (2004) - *Drainage of ice-contact Miage Lake (Mont Blanc Massif, Italy) in September 2004*. Geografia Fisica e Dinamica Quaternaria, 27, 113-119.

DERONDE B., HOUTHUYS R., HENRIET J.P. & VAN LANCKER V. (2008) - *Monitoring of sediment dynamics along a sandy shoreline by means of airborne hyperspectral remote sensing and LiDAR: a case study in Belgium*. Earth Surface Processes and Landforms, 33, 280-294.

DOWNWARD S.R., GURNELL A.M. & BROOKES A. (1994) - *A methodology for quantifying river channel planform change using GIS*. Proceedings of the Canberra Symposium, December 1994 «Variability in Stream Erosion and Sediment Transport», IAHS Publ. n. 224, 449-456.

FRENCH J.R. (2003) - *Airborne LiDAR in support of geomorphological and hydraulic model*. Earth Surface Processes and Landforms, 28, 321-335.

GOVI M. (1976) - *Ricerche sui processi di riattivazione delle capacità erosive negli alvei dei torrenti Stura di Lanzo e Orco*. La Ricerca Scientifica, 46 (2), 332-334.

GREGORY K.J. (1987) - *River Channels*. In: Gregory K.J. & Walling D.E. (Eds.) «Human Activity and Environmental Processes» John Wiley & Sons, Chichester, 207-235.

HERITAGE G. & HETHERINGTON D. (2007) - *Towards a protocol for laser scanning in fluvial geomorphology*. Earth Surface Processes and Landforms, 32, 66-74.

HEY R.D. (1997) - *Stable River Morphology*. In: Thorne C.R., Hey R.D. & Newson M.D. (Eds.) «Applied Fluvial Geomorphology for River Engineering and Management», Wiley, Chichester, 223-236.

HILLDALE R.C. & RAFF D. (2008) - *Assessing the ability of airborne LiDAR to map river bathymetry*. Earth Surface Processes and Landforms, 33, 773-783.

HOFTON M.A. & BLAIR J.B. (2002) - *Laser altimeter return pulse correlation: a method for detecting surface topographic change*. Journal of Geodynamics, 34 (3-4), 477-489.

HUGHES M.L., MCDOWEL P.F. & MARCUS W.A. (2006) - *Accuracy assessment of georectified aerial photographs: implications for measuring lateral channel movement in a GIS*. Geomorphology, 74, 1-16.

JAMES L.A. & MARCUS W.A. (Eds.) (2007) - *The Human Role in Changing Fluvial Systems*. 37th International Binghamton Geomorphology Symposium, Columbia, South Carolina, October 20-22, 2006. Geomorphology, 79 (3-4), 143-506.

KRAUS H. & PFEIFER N. (1998) - *Determination of terrain models in wooded areas with airborne laser scanner data*. ISPRS Journal of Photogrammetry & Remote Sensing, 53 (4), 193-203.

KWAK D.A., LEE W.K., LEE J.H., BIGING G.S. & GONG P. (2007) - *Detection of individual trees and estimation of tree height using LiDAR data*. Journal of Forest Research, 12, 425-434.

LANE S.N., WESTAWAY R.M. & HICKS D.M. (2003) - *Estimation on erosion and deposition volumes in a large, gravel-bed, braided river using synoptic remote sensing*. Earth Surface Processes and Landforms, 28, 249-271.

LIÉBAULT F. & PIÉGAY H. (2001) - *Assessment of channel changes due to long-term bedload supply decrease, Roubion River, France*. Geomorphology, 36, 167-186.

LIÉBAULT F. & PIÉGAY H. (2002) - *Causes of 20th century channel narrowing in mountain and piedmont rivers of southeastern France*. Earth Surface Processes and Landforms, 27, 425-444.

LOLLINO G., ALLASIA P., BALDO M. & GIORDAN D. (2005a) - *Sperimentazione di metodologie innovative per il monitoraggio delle variazioni morfologiche di tratti fluviali: il caso del Torrente Orco*. Atti della 9a Conferenza Nazionale ASITA, Catania, 15-18 Novembre 2005, Associazioni Scientifiche per le Informazioni Territoriali e Ambientali, Milano, II, 1363-1368.

LOLLINO G., BALDO M., GIORDAN D. & ALLASIA P. (2005b) - *New methodology to evaluate morphological changes of river reaches: the case of Orco River (Piedmont, Italy)*. International Conference of Reservoir Operation & River Management (ICROM'05), Guangzhou and Three Gorge (China), September 17-23, 2005, Sun Yat-Sen University, Guangzhou and Three Gorge, 8 pp.

LOLLINO G., ALLASIA P., AUDISIO C., BALDO M., GIORDAN D., GODONE F., GUGLIELMI E., NIGRELLI G. & RIVAROSSA C. (2007) - *Monitoraggio morfologico e sedimentologico finalizzato a una corretta attività e manutenzione dei corsi d'acqua-Relazione Finale*. Convenzione tra Agenzia Interregionale per il Fiume Po (AIPO) e CNR-IRPI di Torino (Rep. n. 92 del 20 luglio 2004).

LOLLINO G., GIORDAN D., BALDO M., ALLASIA P. & PELLEGRINI F. (2008) - *L'uso dei modelli digitali del terreno come strumento per lo studio dell'evoluzione morfologica dei corsi d'acqua: proposte metodologiche e primi risultati*. Il Quaternario, 21 (1B), 331-342.

MARAGA F. (1989) - *Ambiente fluviale in trasformazione: l'alveo-tipo pluricursale verso un nuovo modellamento nell'alta pianura padana*. Proceeding of the International Congress on Geoengineering «Suolosottosuolo», Torino 27-30 Settembre 1989, Associazione Mineraria Subalpina, Torino, 1, 119-128.

McIntosh K. & Krupnik A. (2002) - *Integration of laser-derived DSMs and matched image edges for generating an accurate surface model*. ISPRS Journal of Photogrammetry & Remote Sensing, 56 (3), 167-176.

Milan D.J., Heritage G.L. & Hetherington D. (2007) - *Application of a 3D laser scanner in the assessment of erosion and deposition volumes and channel changes in a proglacial river*. Earth Surface Processes and Landforms, 32, 1657-1674.

Murakami H., Nakagawa K., Hasegawa H., Shibata T. & Iwanami E. (1999) - *Change detection of buildings using an airborne laser scanner*. ISPRS Journal of Photogrammetry & Remote Sensing, 54 (2-3), 148-152.

Naesset E. (1997) - *Estimating timber volume of forest stands using airborne laser scanner data*. Remote Sensing of Environment, 61 (2), 246-253.

Notebaert B., Verstraeten G., Govers G. & Poesen J. (2009) - *Qualitative and quantitative applications of LiDAR imagery in fluvial geomorphology*. Earth Surface Processes and Landforms, 34, 217-231.

Pellegrini L., Maraga F., Turitto O., Audisio C. & Duci G. (2008) - *Evoluzione morfologica di alvei fluviali mobili nel settore occidentale del Bacino Padano*. Il Quaternario, 21 (1B), 251-265.

Pellegrini M., Perego S. & Tagliavini S. (1979) - *La situazione morfologica degli alvei affluenti emiliani del Po*. Estratto dagli Atti del Convegno di Idraulica Padana, Parma 19-20 Ottobre 1979, Magistrato per il Po, Parma, 9 pp.

Rinaldi M. (2003) - *Recent channel adjustment in Italian rivers of Tuscany, central Italy*. Earth Surface Processes and Landforms, 28, 587-608.

Rinaldi M., Teruggi L.B., Simoncini G. & Nardi L. (2008) - *Dinamica recente ed attuale di alvei fluviali: alcuni casi di studio appenninici (Italia centro-settentrionale)*. Il Quaternario, 21 (1B), 291-302.

Smith L.M. & Winkley B.R. (1996) - *The response of the Lower Mississippi River to river engineering*. Engineering Geology, 45, 433-455.

Studio Associato Ser.P.I. (2005) - *Lavori di sistemazione idraulica del Torrente Orco a monte e a valle del Ponte Pedemontana in comune di Salassa (TO) - Indagini propedeutiche*. Convenzione AIPO n. 7 del 14.02.2003, 2 tavv., 19 sezioni.

Surian N. (2006) - *Effect of human impact on braided river morphology: examples from northern Italy*. In: Sambrook Smith G.H., Best J.L., Bristow C.S. & Petts G.E. (Eds.) «Braided Rivers: Process, Deposits, Ecology and Management», Blackwell Publishing, Oxford, 327-338.

Surian N. & Cisotto A. (2007) - *Channel adjustments, bed load transport and sediment sources in a gravel-bed river, Brenta River, Italy*. Earth Surface Processes and Landforms, 32, 1641-1656.

Surian N. & Rinaldi M. (2003) - *Morphological response to river engineering and management in alluvial channels in Italy*. Geomorphology, 50, 307-326.

Surian N. & Rinaldi M. (2004) - *Channel adjustments in response to human alteration of sediment fluxes: examples from Italian rivers.* Proceedings of a Symposium «Sediment Transfer through the Fluvial System» held in Moscow, August 2004, IAHS Publ. n. 288, 276-282.

Surian N., Ziliani L., Cibien L., Cisotto A. & Baruffi F. (2008) - *Variazioni morfologiche degli alvei dei principali corsi d'acqua Veneto-Friulani negli ultimi 200 anni*. Il Quaternario, 21 (1B), 279-290.

Surian N., Rinaldi M., Pellegrini L., Audisio C., Maraga F., Teruggi L., Turitto O. & Ziliani L. (2009a) - *Channel adjustments in northern and central Italy over the last 200 years*. In: James L.A., Rathburn S.L. & Whittecar G.R. (Eds.) «Management and Restoration of Fluvial Systems with Broad Historical Changes and Human Impact». Geological Society of America Special Paper 451, 83-95.

Surian N., Pasqualini D. & Tunis G. (2009b) - *La dinamica dell'alveo del Torrente Torre (Pianura Friulana) nel corso degli ultimi 200 anni*. Memorie della Società Geografica Italiana, 87, 415-426.

Thorne C.R. (1997) - *Channel types and morphological classification*. In: Thorne C.R., Hey R.D. & Newson M.D. (Eds.) «Applied Fluvial Geomorphology for River Engineering and Management», John Wiley & Sons, Chichester, 175-222.

Turitto O. & Audisio C. (2005) - *Analisi dei motivi naturali e antropici all'origine di modificazioni planimetriche riscontrate lungo l'alveo del Torrente Orco negli ultimi due secoli*. Unpublished Report CNR-IRPI di Torino, R.I. 05/36, 61 pp.

Turitto O. & Audisio C. (2008) - *Ponti e dinamica fluviale. Effetti di reciproca interferenza*. L'Acqua, 2, 7-16.

Turitto O., Audisio C. & Agangi A. (2008) - *Il ruolo svolto da piene straordinarie nel rimodellare la geometria di un alveo fluviale*. Il Quaternario, 21 (1B), 303-315.

Winterbottom S.J. (2000) - *Medium and short-term channel planform changes on Rivers Tay and Tummel, Scotland*. Geomorphology, 34, 195-208.

Whitworth M.Z., Giles D., Anderson I. & Clewett M. (2006) - *Terrestrial laser scanning for applied geoscience studies in the urban environment*. IAEG2006 Paper number 252, 9 pp.

Young A.P. & Ashford S.A. (2008) - *Instability investigation of cantilevered seacliffs*. Earth Surface Processes and Landforms, 33, 1661-1677.

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