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BED-LEVEL ADJUSTMENTS IN THE PO RIVER CATCHMENT (NORTHERN ITALY)

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EXTENDED ABSTRACT

Le variazioni morfologiche altimetriche e planimetriche degli alvei fluviali hanno numerosi impatti sulle attività antropiche, quali destabilizzazione di strutture (ponti, briglie, difese di sponda), instabilità delle sponde con possibili rotture arginali, alterazioni dei rapporti fiume-falda e modificazioni della capacità della sezione di contenimento delle piene con effetti sul rischio idraulico. L'analisi delle variazioni morfologiche di alvei fluviali è usata in maniera crescente nella diagnosi delle condizioni dei corsi d'acqua, sia per gli aspetti legati alla qualità degli ecosistemi che per quelli riguardanti le condizioni di pericolosità da dinamica d'alveo.

In Italia la conoscenza delle variazioni morfologiche di alvei fluviali durante gli ultimi 100-200 anni è piuttosto ampia, ma nel caso del Fiume Po e della maggior parte dei suoi affluenti esiste una certa carenza di dati sulle variazioni altimetriche. Gli obiettivi di questo studio sono in primo luogo quello di fornire nuovi dati e conoscenze relativamente alle variazioni altimetriche del Fiume Po e di altri corsi d'acqua compresi all'interno del suo bacino idrografico, ed in secondo luogo quello di discutere le relazioni tra variazioni altimetriche e planimetriche.

L'analisi delle variazioni della quota del fondo ha riguardato il Po e 11 corsi d'acqua all'interno del suo bacino, per un totale di 21 segmenti (macrotratti di lunghezza dell'ordine delle decine di km), ed è consistita nel confrontare due o più rilievi di sezioni trasversali, nell'arco di un periodo che copre gli ultimi 70 anni circa. Per gli stessi segmenti è stato effettuato un confronto tra due sets di foto aeree relativi allo stesso intervallo di tempo per discutere le relazioni tra variazioni di quota del fondo e variazioni planimetriche.

I risultati mostrano come l'abbassamento della quota del fondo risulti largamente prevalente, riguardando 20 dei 21 segmenti analizzati, con valori medi a scala di segmento compresi tra 0.27 m e 5.49 m, e valori massimi a scala di sezione compresi tra 2.37 m e 12.08 m. L'incisione è stata più intensa durante una prima fase (primi decenni successivi al 1950). In particolare, è stato osservato un primo periodo di abbassamento più intenso seguito, in 7 casi, da una fase di inversione di tendenza, a sua volta seguita in 5 casi su 7 da una fase di ulteriore incisione. In un solo caso (segmento di bassa pianura del Fiume Secchia) la prima fase di incisione non è documentata mentre risulta complessivamente una sedimentazione del fondo media a scala di segmento di 0.23 m.

Dall'analisi delle variazioni planimetriche da foto aeree risulta che in tutti i casi si sia verificato un restringimento dell'alveo, con riduzioni di larghezza a scala di segmento che variano tra 21.3 m e 410.1 m. Nel 31% della lunghezza totale dei segmenti analizzati si sono verificate variazioni della morfologia dell'alveo, con il caso più frequente rappresentato dal passaggio da un alveo transizionale ad uno a canale singolo. I casi di variazione da canali intrecciati a canale singolo e a transizionale sono quelli associati con i più alti gradi di restringimento (76.1% e 53.7% della larghezza iniziale rispettivamente), mentre il passaggio da transizionale a canale singolo è quello associato all'incisione media più elevata (3.4 m).

Sulla base di questi dati, è stato ricavato uno schema evolutivo riassuntivo che rappresenta una applicazione del modello originario di Surian & Rinaldi sviluppato a scala nazionale ai corsi d'acqua alluvionali del bacino del Fiume Po. In linea generale, la casistica nel modello originario è confermata dai dati relativi al bacino del Fiume Po, ma con le seguenti differenze: (1) il caso di variazione di morfologia da canali intrecciati a canale singolo non era riportata nel modello originario; (2) il grado di incisione di fiumi inizialmente a canale singolo è più basso rispetto ai casi di fiumi a canale singolo derivanti da morfologie a canali intrecciati o transizionali.

ABSTRACT

An analysis of bed elevation changes by comparing two or more sets of bed profiles was carried out along the Po River and 11 other streams of its catchment, totalling 21 segments, over a period covering approximately the past 70 years. A comparison of two sets of aerial photos, taken during the same period, was also carried out with a view to discussing relations between bed-level and planform adjustments.

The results showed that bed incision was ubiquitous in all rivers, occurring in 20 out of 21 segments, with segment-averaged values of 0.27 to 5.49 m and at-a-site values of 2.37 to 12.08 m. A first period of major bed lowering (during the first few decades after 1950) was followed by a trend reversal in 7 out of 21 cases, whereas aggradation was followed by further incision in 5 cases.

The results of changes in channel width and planform pattern showed that narrowing occurred in all cases and that changes in channel morphology occurred in 31% of the total analysed river length, the most frequent case being a change from transitional to single-thread. Changes from an initial multi-thread to a transitional or single-thread morphology were associated with a higher degree of narrowing, whereas changes from a transitional to a single-thread morphology were associated with the highest degree of bed lowering. A summary evolutionary model was derived, representing an application of the original Surian and Rinaldi model to the alluvial rivers of the Po River catchment.

Keywords: *incision, bed-level lowering, channel narrowing, channel adjustments*

INTRODUCTION

Bed-level adjustments (incision, degradation, aggradation) generally occur along disturbed alluvial rivers that are free to adjust their boundaries because of an imbalance between the amount of flow energy or stream power and sediment load being delivered from upstream (Simon & Rinaldi, 2006). Bed incision and other types of channel adjustment may have important consequences on human artefacts and involve flood risks, such as scour of crossing structures, bank instability, levee failure, modification of hydraulic cross-sections and of flood capacity, as well as alterations of physical habitats and ecosystems. Analysis of channel changes is increasingly used for investigating river conditions, assessing the quality of related ecosystems, and identifying channel dynamics hazards (Rinaldi *et alii*, 2015). Therefore, knowledge of past and recent channel adjustments is increasingly becoming a fundamental component of river and flood risk analysis and management.

In Italy, several studies have documented bed incision related to a variety of human disturbances. Some studies have focused on the overall morphological response to river engineering and management at national or regional scales (Surian & Rinaldi, 2003; Rinaldi, 2003; Surian *et alii*, 2009; Scorpio *et alii*, 2015; Bizzi *et alii*, 2019). Other research has focused on morphological changes of specific rivers (e.g. Rinaldi & Simon, 1998; Pellegrini *et alii*, 2008; Cencetti & Fredduzzi, 2008; Preciso *et alii*, 2011; Ziliani & Surian, 2012; Magliulo *et alii*, 2013, 2021; Bollati *et alii*, 2014; Scorpio & Rosskopf, 2016; Cencetti *et alii*, 2017; Scorpio *et alii*, 2018a; Scorpio & Piégay, 2021). In these studies, quantitative data on bed-level adjustments are less frequently available than multitemporal changes in channel width and other planform characteristics, since aerial photos are more widely available than topographic surveys (necessary for investigating bed-level changes).

In the case of the Po River, the largest river in Italy, historical planform changes have been extensively documented (e.g. Braga & Gervasoni, 1989; Castaldini & Piacente, 1995; Marchetti, 2002). However, the amount of published data concerning its bed-level adjustments in the last century is limited (Tacconi & Billi, 1990; Lamberti & Schippa, 1994). For these reasons, studies based on unpublished quantitative data of bed-level adjustments in the Po River catchment can provide important insights into current knowledge.

The objectives of this study are (1) to provide new data concerning bed-level adjustments in the Po River catchment, and (2) to discuss relations between bed-level and planform adjustments, testing previous models of channel evolution developed for Italian rivers.

STUDY AREA

The Po River catchment (Fig. 1), the largest of Italy (73974 km^2), can be divided into three main sectors: (1) the northern and western Alpine sector, mostly consisting of crystalline metamorphic rocks; (2) the southern Apennine sector, mostly consisting of sedimentary rocks; and (3) the Padan Plain, made up of fluvial, glacial, and delta sediments of Quaternary age.

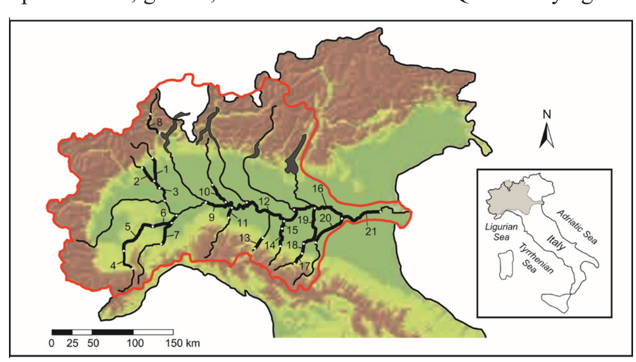

Fig. 1 - Study area with the selected 21 segments (segment numbers refer to Tab. 2)

In addition to the Po River, 11 other streams included in its catchment were selected based on available bed profiles, covering a wide range of subcatchment sizes, river lengths, basin relief, and mean annual discharge (Tab. 1).

River	Catchment area (km^2)	River length (km)	Basin relief (m)	Mean annual discharge ($m^3 s^{-1}$)
Po	73974	652	4808	1506
Lambro	1350	130	1401	40.6
Toce	1778	84	2689	70
Sesia	3038	140	4540	70.4
Cervo	1024	65	2472	21.7
Tanaro	8175	276	2131	116.1
Bormida	2663	153	987	40
Trebbia	1070	120	1406	35
Taro	2026	126	1717	42.4
Enza	890	112	1408	12.1
Secchia	2174	172	2011	42
Panaro	1783	165	2157	19

Tab. 1 - Main physical characteristics of river catchments

For each selected river, bed-level adjustments were analysed at the segment scale, a segment being defined as a macroreach (with a length in the range of tens of km) located within a distinct physiographic context and with relatively homogeneous characteristics in terms of valley setting (according to Rinaldi *et alii*, 2015). Excluding confined segments because of their limited possibility of adjustments, two physiographic contexts were considered: (1) hilly-mountainous; and (2) alluvial plain. Hilly-mountainous segments may be (1) partly confined within a narrow and/or discontinuous alluvial plain, or (2) unconfined within a continuous but narrow plain (generally <2 km in width) included in a hilly-mountainous area. As regards alluvial plains, two types of segment were considered: (1) high plains, coinciding with plains of higher gradient starting from the outlet of hilly-mountainous segments (e.g. along alluvial fans); and (2) low plains, characterised by a lower gradient (normally <0.0015) and a finer sediment. A summary of the main characteristics of the 21 selected river segments is reported in Table 2.

N_S	*R*	*PU*	L_S (km)	L_A (km, %)	*CM*	*W* (m)	*S* (m/m)
1	Sesia	*HP*	41.5	41.5 (100%)	*WA – B*	263.8	0.0035
2	Cervo	*HP*	28.2	26.7 (94%)	*S*	62.2	0.0024
3	Sesia	*LP*	33.9	33.9 (100%)	*S – M*	150.8	0.0006
4	Tanaro	*HM PC*	71.3	67.7 (95%)	*M – S*	57.2	0.0027
5	Tanaro	*HM UN*	62.1	62.1 (100%)	*S – M*	97.7	0.0015
6	Tanaro	*LP*	59.9	59.9 (100%)	*M*	83.5	0.0004
7	Bormida	*LP*	38.7	38.7 (100%)	*M – S*	46.3	0.0009
8	Toce	*HM PC*	43.2	41.7 (97%)	*WA – S*	127.1	0.0026
9	Po	*LP*	94.1	94.1 (100%)	*M – S*	391.4	0.0002
10	Lambro	*LP*	46.7	22.8 (49%)	*M – S*	41.4	0.0008
11	Trebbia	*HP*	22.1	22.1 (100%)	*WA*	276.0	0.0037
12	Po	*LP*	100.9	100.9 (100%)	*S*	335.3	0.0002
13	Taro	*HM PC*	12.2	4.7 (39%)	*B – WA*	378.6	0.0054
14	Enza	*HP*	24.8	24.8 (100%)	*WA – S – SAB*	75.7	0.0047
15	Enza	*LP*	25.3	11.8 (70%)	*M*	15.5	0.0007
16	Po	*LP*	82.3	82.3 (100%)	*S– WA*	430.9	0.0002
17	Secchia	*HM PC*	15.6	6.2 (100%)	*B – S*	187.7	0.0063
18	Secchia	*HP*	17.9	17.9 (100%)	*WA – S*	110.0	0.0044
19	Secchia	*LP*	82.5	82.5 (100%)	*S – M*	13.0	0.0003
20	Panaro	*LP*	65.0	65.0 (100%)	*S – M*	19.5	0.0003
21	Po	*LP*	58.8	58.8 (100%)	*S*	395.9	0.0001

Tab. 2 - Summary of the main characteristics of the analysed river segments. NS: segment number; R: river; PU: physiographic unit, where HP = High Plain, LP = Low Plain, HM = Hilly-Mountainous Area, PC = partly confined, UN = unconfined setting; LS: total segment length; LA: length of the segment portion with available bed profiles (percentage of total segment length between parentheses); CM: channel morphology, where B = braided, M = meandering, S = sinuous, SAB = sinuous with alternate bars, WA = wandering; W: channel width; S: bed slope

DATA COLLECTION AND METHODS

The study was based on the analysis of existing topographic cross-sections or bed profiles consisting of open data from an existing geoportal (geoportale.agenziapo.it) and integrated, for the case of the Trebbia River, with data derived from a previous study (Bollati *et alii*, 2014). A flow chart summarising the various methodological phases is reported in Fig. 2.

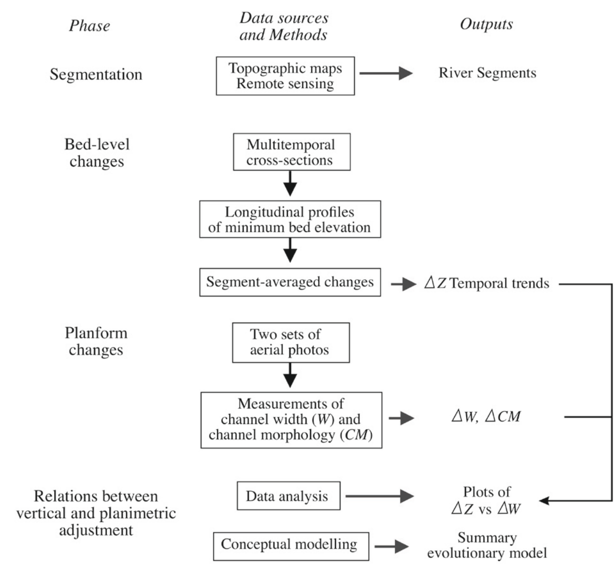

Fig. 2 - Methodological flow chart

The two criteria for selecting river segments were as follows: (1) a minimum of two sets of cross-sections or bed profiles, and (2) a time interval between the first and last survey of at least 20 years. The study was focused on the period after 1950, with a first survey between the 1950s and the early 1970s, and a second or last survey around the beginning of the 2000s. Based on these criteria, a total of 966.1 km in the Po River catchment were analysed (Table 2).

Progressive distances of cross-sections along rivers were already available from the geoportal. In some rivers, cross-sections were resurveyed at the same positions as in the previous survey; in other cases, the positions of some cross-sections in different years were different.

For each year with available data, the longitudinal profile was obtained by plotting the minimum bed elevation against the downstream distance for each cross-section. The change in minimum bed elevation for each pair of surveys was then obtained by the difference of areas (bed elevation against downstream distance) underlying the two profiles, reflecting the net result of incision and aggradation, divided by the length of the profile. Then, a temporal trend of segment-averaged bed elevation changes was derived. Furthermore, the maximum value of local (at-a-site) bed change was also obtained by comparing cross-sections surveyed at about the same position.

After analysing bed elevation changes, the overall changes in channel width and morphological pattern during the period of analysis were also evaluated, with a view to investigating possible relations between vertical and planimetric adjustments. With regard to channel width, i.e. the width of the single low-flow channels plus that of unvegetated or sparsely vegetated bars, measurements from available aerial photos and orthophotos were carried out, and a segment-averaged channel width was obtained for each analysed year. Two years were analysed: (1) 1954, given the availability of an aerial flight (Volo GAI, Istituto Geografico Militare, scale 1:33000) covering the entire country and representing the situation before the phase of the analysed bed adjustments; and (2) the available orthophoto of the closest year following the last topographic survey (scale generally of 1:10000). According to similar studies (e.g. Surian *et alii*, 2009; Rinaldi *et alii*, 2009), an error margin of 6 m was assumed for each measurement of channel width.

As for channel morphology, morphological types along the segment were classified based on the same aerial photos, distinguishing three broad categories: (1) multi-thread (braided); (2) transitional (wandering and sinuous with alternate bars); and (3) single-thread (sinuous and meandering). If additional morphological types arose in the same year, then the percentage of segment length for each morphology was calculated.

RESULTS

Plots of changes in bed elevation over time for each segment represented the starting point of our analysis. A preliminary analysis showed that, in most cases, the first two available sets of data revealed a bed incision, which was, therefore, the first type of bed adjustment during that period. This was followed in some cases by a trend reversal, with a period of aggradation, and eventually by a late interval of further incision.

To facilitate classification and data analysis, the evolutionary trends were divided using the following annotations: (1) *T1* is defined as the first available year; (2) *T2* represents the end of the period of incision and the first year of the period of trend reversal, if any; and (3) *T3* is the end of the trend reversal period.

Table 3 summarises the results, whereas Figs. 3 and 4 display adjustment trends and overall changes.

The initial period of incision is documented for 20 out of 21 cases, with segment-averaged values of bed-level lowering ranging from 0.27 m to 5.49 m. The trend reversal is documented for 7 cases, with a time of onset ranging from 1979 to 2003. In just one case (segment 19), the first period of incision is missing or was not identified based on available data, and only a phase of aggradation was recorded starting from 1969. In 5 out of 7 cases, aggradation was followed by

N_S	Period of Incision				Period of Aggradation (including late incision)					Overall period	
	T_1	T_2	ΔZ (m)	ΔZ_S (m)	*AD*	T_2	T_3	ΔZ (m)	ΔZ_S (m)	ΔZ (m)	ΔZ_S (m)
1	1971	2003	−1.75	−3.62						−1.75	−3.62
2	1971	2003	−2.71	−4.16						−2.71	−4.16
3	1962	2003	−1.34	-−4.84						−1.34	−4.84
4	1973	2001	−2.33	−12.08						−2.33	−12.08
5	1973	2005	−1.91	−8.11						−1.91	−8.11
6	1973	2005	−0.42	−3.84						−0.42	−3.84
7	1972	2004	−3.21	−4.81						−3.21	−4.81
8	1979	2002	−3.24	−8.04						−3.24	−8.04
9	1954		−2.49	−5.07	A	1979	2005	0.01	2.60	−2.48	−5.17
10	1956	2002	−3.24	−3.66						−3.24	−3.66
11	1974		−1.69	n.a.	A	2003	2009	0.07	n.a.	−1.62	n.a.
12	1954		−3.87	−6.34	I	1979	2005	−0.02	−2.73	−3.89	−6.42
13	1973	2005	−1.16	−2.37						−1.16	−2.37
14	1973	2011	−4.05	−8.11						−4.05	−8.11
15	1973	2011	−0.27	−2.41						−0.27	−2.41
16	1954		−3.29	−9.61	A	1979	2005	1.53	8.79	−1.76	−9.86
17	1969	2002	−5.49	−10.83						−5.49	−10.83
18	1969		−3.30	−11.46	A	1992	2002	1.17	5.47	−2.13	−6.99
19					A	1969	2015	0.23	3.34	0.23	3.34
20	1969	1991	−0.41	−3.60	I	1991	2017	−0.25	−2.75	−0.66	−4.48
21	1954		−2.54	−4.92	I	1979	2005	−0.11	−0.81	−2.65	−4.05

Tab. 3 - Summary of changes in bed elevation, during the period of incision (T1-T2 interval) and the following period of trend reversal (T2-T3 interval). NS: segment number; T1: first available year; T2: end of the period of incision and first year of the period of trend reversal, if any; T3: end of the period of trend reversal, if any; ΔZ: segment-averaged bed level change during a given interval; ΔZS: maximum at-a-site bed-level change during the interval; n.a.: data not available; AD: net adjustment during the T2-T3 interval, where A = aggradation, I = incisio

a late period of new incision, but with only 3 cases where the net change in the reversal period was bed lowering. Segment-averaged values in the overall period of trend reversal ranged from 0.25 m of net incision to 1.53 m of net aggradation.

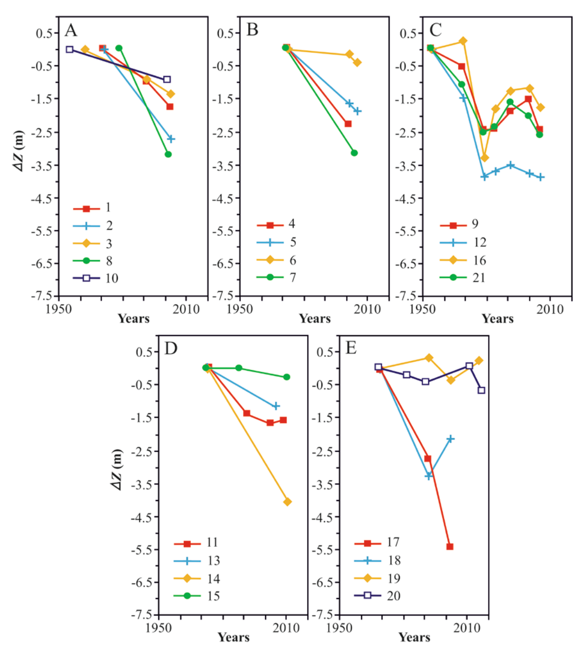

Fig. 3 - Trends of bed-level adjustment for the 21 river segments (segment numbers refer to Tab. 2). A, B, D, and E: Po subcatchments; C: Po River

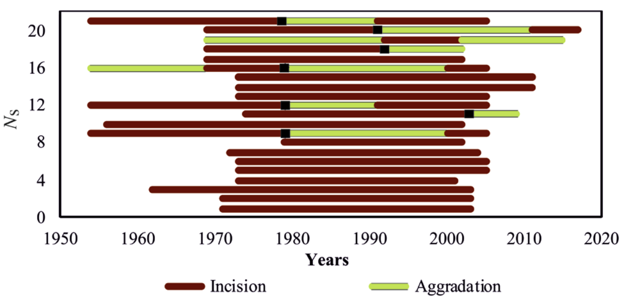

Fig. 4 - Temporal sequence of bed adjustments for each segment. Ns: segment number

The frequency distribution of total changes during the entire period (Fig. 5) clearly showed that incision was the largely predominant overall change, with the highest number of cases falling between 1.5 m and 2 m of bed lowering.

Maximum at-a-site values of bed-level lowering were very impressive. For the period of incision, they ranged from 2.41 m to over 10 m (segments 4, 17, and 18). For the period of trend reversal, intense local aggradation occurred in some cases (generally upstream of transversal structures), reaching an impressive value of 8.79 m (segment 16) along the Po River. Maximum at-a-site values in the overall period showed a net incision for 20 out of 21 cases, ranging from 2.37 m to 12.08 m. In the single case where incision was not recorded (segment 19), the maximum value of aggradation was 3.34 m.

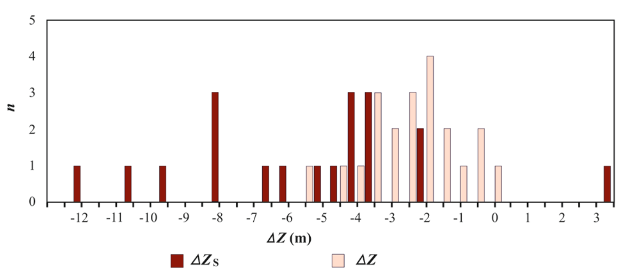

Fig. 5 - Number of cases for each class of 0.5 m bed-level changes, where ΔZ_S and ΔZ: maximum at-a-site and segment-averaged changes during the overall period, respectively

The amount of change was similar in each of the three physiographic units; however, the case with the highest incision was located in the hilly-mountainous area (-5.49 m, segment 17), whereas the only case of net aggradation occurred in low plains. Cases with the occurrence of a trend reversal were located mostly along low plains (4 segments) and, to a lesser extent, in high plains (3 segments).

The results of the analysis of planform changes are summarised in Tab. 4. Three segments (15, 19, 20) with a small channel width that was not reliably measurable (i.e. <35 m on the aerial photos of 1954 and/or <25 m on the orthophotos of the last survey) were excluded from this analysis. Finally, changes in bed elevation vs.

N_S	1954				1999 – 2017				
	W (m)	*CM* (%)			t_2	*W* (m)	*CM* (%)		
		MT	*T*	*ST*			*MT*	*T*	*ST*
1	341.6	65	35		2010	263.8	18	82	
2	114.9		100		2004	62.2			100
3	218.5		28.5	71.5	2003	150.8			100
4	78.3			100	2012	57.2			100
5	140.0			100	2012	97.7			100
6	106.6			100	2011	83.5			100
7	60.5			100	2013	46.3			100
8	185.7	27.3	28.1	44.6	2007	140.9	7.3	39	53.7
9	491.6		5.9	95.1	2007	391.4			100
10	50.4			100	2003	41.4			100
11	501.6	100			2010	276.0	16	84	
12	745.4		100		2007	335.3			100
13	566.7	100			2003	362.2	100		
14	281.1	63.1	36.9		2017	75.7		56.7	43.3
15	n.m.			100	2017	n.m.			100
16	499.2		56.6	43.4	2007	430.9		35.7	64.3
17	333.6	100			2011	185.4	52.9	47.1	
18	374.6	100			2003	104.6	40.2		59.8
19	n.m.	3.5	2.5	94	2017	n.m.			100
20	n.m.			100	2017	n.m.			100
21	431.4			100	2011	395.9			100

Tab. 4 - Summary of changes in channel width and morphology. NS: segment number; W: channel width; CM: channel morphology, in % of segment length, where MT = multi-thread (braided); T = transitional (wandering, including sinuous with alternate bars); ST = single-thread (sinuous and meandering); t2: year of second orthophoto; n.m.= not measurable because of the small size of the river

changes in channel width, including the error margins associated with measurements of channel width (assumed to be a maximum of 6 m for each measurement), are reported in Fig. 6, where data is grouped according to different initial (1954) channel morphologies. The graph highlights the following features: (1) in

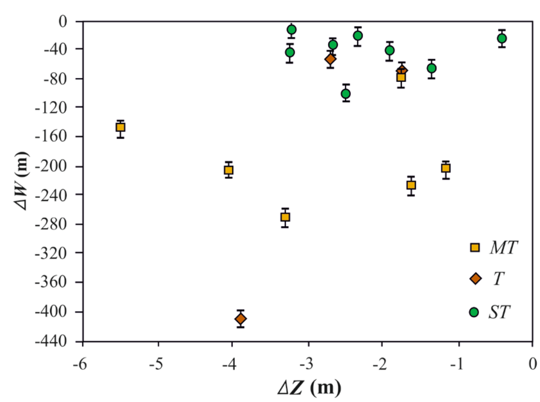

Fig. 6 - Changes in bed elevation (ΔZ) vs. changes in channel width (ΔW), with segments grouped on the basis of prevailing initial channel morphology, where MT = multi-thread, T = transitional, and ST = single-thread. Vertical error bars indicate the error margins related to measurements of channel width from aerial photos

all cases, the channel reduced its width from 1954 to the second survey; (2) except in one case (segment 12, Po River, with a *ΔW* = -410.1 m), segments with a single-thread and transitional initial morphology were characterised by similar amounts of narrowing, and lower than in the cases of initial braided morphology. The latter cases had a channel narrowing always >80 m, and >150 m in 6 out of 7 cases.

As regards changes in channel pattern, a further analysis was carried out by defining six classes based on the initial (1954) and final (1999-2017) channel morphology. Segments including two or more classes were divided into reaches with a homogeneous class, and changes in channel width and bed elevation for each reach were calculated. For each class, the mean change in channel width and bed elevation was then calculated. From the results of this analysis, the following features can be observed (Table 5): (1) the change of channel morphology occurred along roughly 31% of the total analysed river length, the most frequent case being the transformation from transitional to single-thread (22.2% of total length), followed by a passage from multi-thread to transitional (7.3%), and from multi-thread to single-thread (1.7%); (2) changes from multi-thread channels to single-thread and transitional channels were associated with the maximum amounts of channel narrowing (76.1% and 53.7% of initial channel width, respectively), followed by the change from transitional to single-thread (49.2%); (3) the change from transitional to single-thread was associated with the maximum changes in bed elevation (-3.4 m); (4) the three cases of maintenance of the same initial morphology were associated with a similar degree of incision (ranging from 2.1 to 2.2 m); and (5) the maintenance of a single-thread morphology associated with channel narrowing (21.3%) and bed-level lowering (2.1 m) was the most common case, occurring along 454.3 km of river length.

Channel Morphology 1954	1999 – 2017	*N*	L_{TOT} (km)	ΔW (%)	ΔZ (m)
MT	*MT*	6	26.3	−38.7	−2.1
MT	*T*	4	56.7	−53.7	−2.2
MT	*ST*	5	13.6	−76.1	−2.9
T	*T*	3	55.6	−15.2	−2.2
T	*ST*	7	172.7	−49.2	−3.4
ST	*ST*	9	454.3	−21.3	−2.1

Tab. 5 - *Summary of changes in channel morphology: mean changes in channel width and bed elevation for each of the six classes of initial (1954) and final (1999-2017) channel patterns. MT: multi-thread (braided); T: transitional (wandering, including sinuous with alternate bars); ST: single-thread; N: number of reaches for each class; L_{TOT}: total length of reaches for each class (segments with changes in channel width lower than the error margin are excluded); ΔW: change in channel width (expressed as a percentage of initial width); ΔZ: net bed-level change during the overall period*

DISCUSSION

Trends and amounts of bed-level adjustments

Bed incision was the largely predominant type of bed adjustment along the Po River and the other investigated streams of its catchment, with aggradation occurring in some cases but in lower amounts. Previous research on Italian rivers has already indicated incision as the predominant type of bed-level adjustment, together with channel narrowing, identifying two distinct phases (named phases I and II), with the first phase starting in about 1900 and the second phase in about 1950 (Rinaldi & Simon, 1998; Surian & Rinaldi, 2003; Surian *et alii*, 2009; Preciso *et alii*, 2011; Ziliani & Surian, 2012; Scorpio *et alii*, 2015; Scorpio & Rosskopf, 2016). Many of these studies also described a third phase (named phase III) of trend reversal in channel width and/or bed elevation, generally starting in the 1990s (e.g. Rinaldi *et alii*, 2009; Surian *et alii*, 2009; Ziliani & Surian, 2012; Bollati *et alii*, 2014; Scorpio *et alii*, 2015; Cencetti *et alii*, 2017; Magliulo *et alii*, 2021).

The data from the above studies reported in this paper was limited to part of phase II and, possibly, phase III. During the period investigated, bed-level lowering was fairly ubiquitous in all rivers of the Po catchment. Most of the changes occurred in many cases from the 1950s-1960s to the end of the 1980s, but they often extended until the beginning of the 2000s and, in a few cases, until the beginning of the 2010s. The amounts of segment-averaged incision recorded in this study fell within the range observed in many other Italian rivers. However, maximum local (at-a-site) values were even higher than those reported in the literature until now. For example, Surian & Rinaldi (2003) pointed out that incision ranging from approximately 2 to 6 m was quite common in Italian alluvial rivers and, in several cases, incision was equal to 10 m or even more.

With regard to the only segment where the initial phase of incision was not recorded (segment 19, low Secchia River), based on existing knowledge (Pellegrini *et alii*, 1979), a severe bed incision was described already before 1969, i.e. the initial time analysed in this study for this river. This finding may explain why the phase of major incision was not detected based on the data available in this study. An alternative explanation is that aggradation actually occurred along the low plain segment of the Secchia River as a result of downstream sedimentation associated with upstream erosion.

As previously noted, after phases of incision and narrowing, several rivers experienced periods of partial bed recovery ('phase III'). In this study, the reversal of the incision trend for the Po River started in 1979, i.e. earlier than the onset of phase III as reported in other studies. However, in part of these cases, an oscillation of bed level rather than a clear recovery took place.

Relations between vertical and planimetric adjustments

The results of this study suggested that the amount of channel narrowing was not clearly associated with the amount of bed incision, but the main controlling factor appeared to be the initial channel morphology, which was in turn associated with different amounts of bedload. Segments with the most significant change in channel width were those characterised by an initial (1954) braided or transitional morphology, i.e., for the same amount of incision, multi-thread and transitional segments adjusted their width much more than single-thread segments.

The results of this study were tested against the evolutionary model proposed by Surian & Rinaldi (2003), which refers to a larger number of rivers and a larger temporal period (overall changes between approximately 1900 and 2000).

Figure 7 displays a summary evolutionary model of the results obtained from this study, where cases of channel adjustments are set in a spatiotemporal, quantitative framework. Starting from the three categories of planform patterns (A, B, and C) of the main temporal interval investigated in this study, six classes of channel adjustments are observed after 1950; each case is placed in the diagram as a function of the mean values of changes in width vs. changes in bed elevation for each class.

The trends of the Surian & Rinaldi (2003) model were generally confirmed, especially the fact that, for the same types of disturbance, multi-thread and transitional channels proved to be more sensitive (Brierley & Fryirs, 2003), i.e. more prone to adjust their morphology to a significant extent in response to perturbations. The main differences from the Surian & Rinaldi model were as follows: (1) the changes from multi-thread to single-thread observed in this study

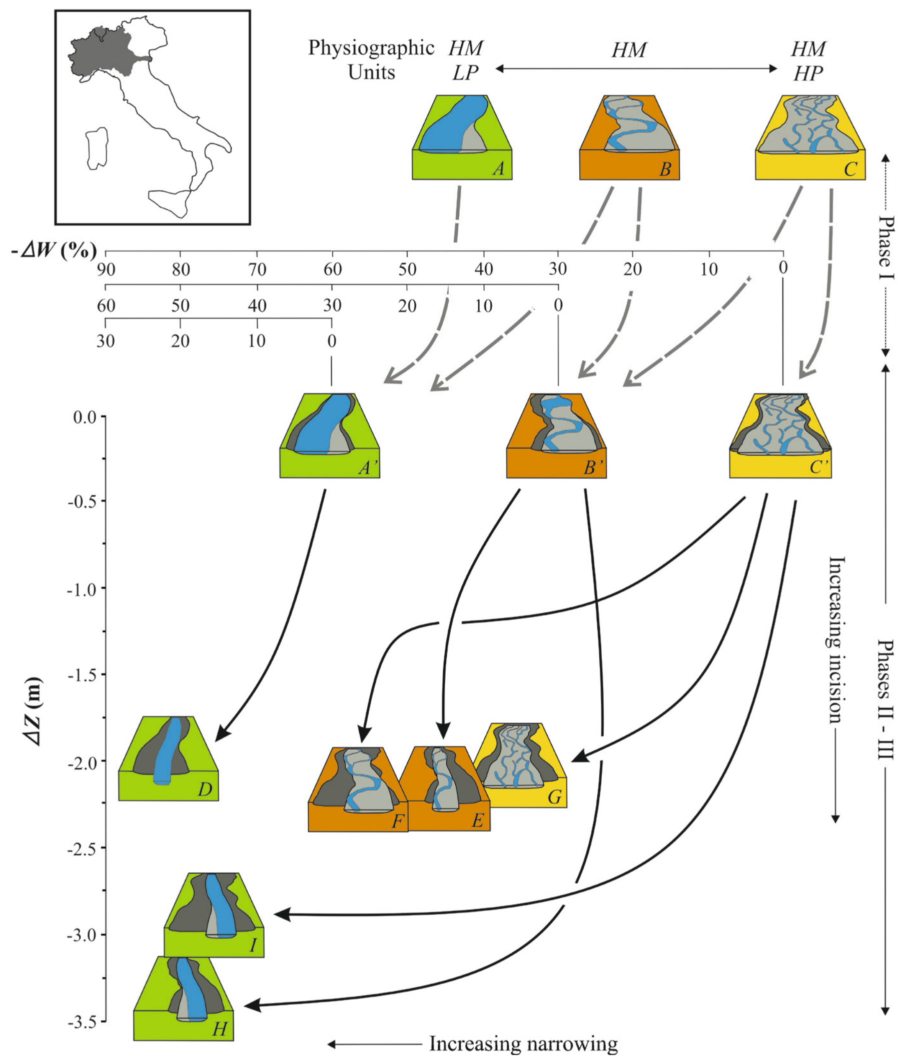

Fig. 7 - Summary model of channel adjustments in the study area. A: changes in channel morphology, channel width (ΔW), and bed elevation (ΔZ). Physiographic units: HM = hilly-mountainous; LP = low plain; HP = high plain. A: initial (1900) single-thread morphology; B: initial (1900) transitional morphology; C: initial (1900) multi-thread morphology; A', B', and C': same morphologies as A, B, and C at the beginning (1950s) of the period of investigation of this study (after phase I); D: incised single-thread channels deriving from initial single-thread channels; E: incised single-thread channels deriving from initial transitional channels; F: incised transitional channels deriving from initial multi-thread channels; G: incised transitional channels deriving from initial transitional channels; H: incised single-thread channels deriving from initial multi-thread channels

were not reported in the original model; and (2) single-thread channels did not change their morphological pattern, but the degree of incision for segments with this initial morphology was in most cases lower than that of single-thread channels deriving from initially braided or transitional morphologies. However, part of these differences may be related to the fact that the changes observed in this study may refer to a time interval shorter than that of the original Surian & Rinaldi model.

Possible causes of adjustment

Understanding cause-effect relations and the influence of human activities relative to natural factors on the trends of channel adjustments is a complex task because of the cumulative impact of multiple drivers acting at different spatial and temporal scales. In most cases, the interpretation of cause-effect relations relies on temporal synchronicity and spatial proximity of channel response to possible causes, and rigorous proofs for cause-effect relationships of cumulative impacts are limited (Downs & Piégay, 2019). For these reasons, a systematic analysis is out of the scope of this paper, but some considerations about the possible causes of adjustment can be outlined.

Several potential causes during approximately the last 150 years can be identified in the Po River catchment, as for other Italian rivers, mainly including: reforestation of upland catchments, reduction in sediment supply by check dams and weirs in the catchment, dams and flow regulation, embankments and other bank protection structures, modifications of channel patterns (meander cut-offs, channelisation), and sediment mining. Interventions at the catchment scale have been generally indicated as the main causes of the first historical period of adjustment, whereas dams and sediment mining have most frequently been indicated as causes during the period analysed (Rinaldi & Simon, 1998; Surian & Rinaldi, 2003; Pellegrini *et alii*, 2008; Surian *et alii*, 2009; Scorpio *et alii*, 2015, 2018a; Scorpio & Rosskopf, 2016; Cencetti *et alii*, 2017). A major role for the onset of the phase of intense channel narrowing, more important than that indicated in previous studies, may have been played by the construction of groynes, very commonly used during the 1950s along the Po River and some of its tributaries.

With regard to the more recent trend reversal (phase III), various studies have suggested that this may be related to the cessation of the intensive phase of sediment mining, promoted in turn by the increased sediment supply from bank erosion during the widening phase (e.g. Rinaldi *et alii*, 2008; Surian *et alii*, 2009; Bollati *et alii*, 2014; Scorpio *et alii*, 2015). However, oscillations following the major phase of incision and narrowing are likely to be transient effects of large floods (Clerici *et alii*, 2015). This hypothesis is also supported by the increasing number of flash floods occurring in Mediterranean countries in recent decades, having large impacts on channel changes such as widening and aggradation (e.g. Surian *et alii*, 2016; Scorpio *et alii*, 2018b).

CONCLUSIONS

Minimum bed elevation profiles obtained from cross-sections were analysed at the segment scale for 12 rivers of the Po River catchment (northern Italy), totalling 21 segments and approximately 966 km of river length over the period 1950-2015.

The results appeared to support existing knowledge on channel adjustments of Italian rivers, but adding some new quantitative information on bed-level changes for the Po River catchment, which was quite limited before this study. Additional details also became available on the linkages between bed-level, width, and channel pattern changes, providing quantitative support to the original model of Surian & Rinaldi (2003). The following main conclusions can be drawn:

(1) incision was the largely dominant type of bed-level adjustment and it was ubiquitous in all river segments (except one), with no significant differences in terms of amounts and temporal trends for the different physiographic units (hilly-mountainous area, high plain, low plain);

(2) as observed in previous studies, the main phase of incision, beginning in the 1950s, was followed, in a number of cases, by a trend reversal; however, aggradation was lower than the previous incision and, in part of the segments, it was followed by a new interval of further incision;

(3) incision was associated with channel narrowing and, in about 31% of the total investigated river length, with changes in channel pattern from multi-thread to transitional or single-thread and from transitional to single-thread channels, whereas initial single-thread channels always maintained their original morphology;

(4) in terms of causes, the results from our study appeared to confirm that a combination of human factors may have caused overall incision, including upland reforestation and torrent control works at the catchment scale, dams, construction of bank protection structures (groynes), and sediment mining, the latter two being the main factors promoting the main phases of narrowing and incision after 1950.

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