The effects of in-stream gravel mining on river incision: an example in Adriatic Central Italy

by

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with 1 photo, 4 figures and 2 tables

Summary. The present paper shows the consequences of intense human activities carried out along the river beds mostly during the XX century. There have been many attempts to quantitatively correlate river incision and suspended/bed load reduction following the construction of river dams, while there are few approaches that take into account the effects of gravel quarrying from the river beds. Using data from several rivers of central and northern Italy and in Europe, a new simple empirical relation, was formulated in order to establish a possible relation between the fluvial erosion capacity consequent to quarrying and the amount of fluvial incision. The preliminary results are very encouraging even though, due to the limited number of available data, the relation needs to be further tested.

Keywords: Fluvial-coastal morphodynamics, human impact, in-stream gravel mining, Adriatic central Italy

1. Introduction

Undoubtedly, fluvial systems are the first geomorphic components of landscape that register the changes of physical environment. The development of drainage systems is controlled by several factors including climate changes (PREECE & BRIDGLAND 1999; BROCARD et al. 2003), eustatic sea-level changes (SCHUMM 1993; HOLBROOK et al. 2006), tectonic uplift (MERRITTS et al. 1994; SCHUMM et al. 2000) and human activities (GARCÌA-RUIZ & VALERO-GARCÈS 1998; SURIAN & RINALDI 2003; HUDSON & KESEL 2000; BUCCOLINI et al. 2007; HUDSON et al. 2008).

Since the early Holocene, erosion and deposition processes have alternately affected the fluvial-coastal systems of Adriatic central Italy mainly as a consequence of climate changes and, only in part, as a direct effect of anthropic activities on the slopes or along the stream channels (DELANO-

SMITH 1979; BUCCOLINI et al. 2010). Starting from the XIX century, most cases of river incision in the temperate regions of the northern hemisphere may be attributed to perturbations of stream beds brought about by development works, embankments and dams (GALAY 1983; WILLIAMS & WOLMAN 1983) although the main factor in recent decades has been the extraction of sediments from channels (GENTILI & PAMBIANCHI 1987; PETIT et al. 1996; BRAVARD et al. 1997; BROWN et al. 1998; MARCHETTI 2002; SIMON & RINALDI 2006; BUCCOLINI et al. 2010; MOSSA & MARKS 2011). In the case of the Adriatic rivers, when mining activities were conducted in the mid-terminal portions of the river itself, also advance and withdrawal phenomena of the mouths were recorded, as a result of changes in the suspended and bed load (MATERAZZI et al. 2010).

Even though several authors have considered the relations between the amount of sediments subtracted from the river by damming and the entity of stream incision (BABIŃSKI 1982; BRAVARD et al. 1997), only few approaches gave a quantitative relation between stream erosion and river bed quarrying. Some authors quantified the effects of gravel mining in river beds in terms of channel incision using: sediment budget analysis (e.g., ROVIRA et al. 2005), hydraulic parameters like shear stress and grain size measurements (e.g., PETIT et al. 1996), mathematical models such as dimensionless exponential functions (e.g. SIMON 1992; RINALDI & SIMON 1998; SIMON & RINALDI 2006), linear diffusion models (MARTÍN-VIDE et al. 2010), or laboratory experiments (e.g., GILL 1994; LEE et al. 1993; CHEN et al. 2010). All these methodologies were applied to stretches of river, considering unitary channel length.

With the present work, we want to give our contribution to the understanding of the effects of gravel mining on fluvial morphodynamic, especially on the erosion-transport-sedimentation mechanisms. These studies are part of a broader framework of policies by the European Commission (Directives 2000/60/EC and 2007/60/EC) aimed at defining the basic principles of water sustainability (both surface and ground waters), river basin management and flood risks assessment and management. Using data from the amount of material quarried on the river beds, we evaluated the influence of gravel mining on the final segments and on the mouths of the main Adriatic rivers of central Italy.

2. Geological-geomorphological setting

The study area belongs to a vast region located in the peri-Adriatic hilly belt (fig.1), mostly made of Miocene, Pliocene and Pleistocene marine sedimentary rocks overlying Messinian turbidites (clayey sediments with frequent intercalations of sands and conglomerates). Along the Adriatic coast this sedimentary sequence ends with extensive coastal to fluvial/deltaic deposit (sands, conglomerates and gravels) of Sicilian–Crotonian age.

Starting from the early Pliocene, the peri-Adriatic sedimentary succession has been incised from west to east by consequent rivers (fig.1) following the regional topographic gradient (DRAMIS et al. 1991). The resulting valleys are strongly asymmetrical, with the northern side characterized by a staircase of alluvial terraces and the southern one usually very steep and affected by a large number of landslides (COLTORTI et al. 1991).

Since the middle Pleistocene four orders of alluvial terraces were produced (COLTORTI et al. 1991). In the inner sectors of the river valleys, the genesis of alluvial terraces was connected to the Pleistocene climatic changes interacting with the river cutting process induced by the regional uplift (CICCACCI et al. 1985; DRAMIS 1992; BARTOLINI et al. 2003). In the external sectors close to the Adriatic coast, the alluvial terraces alternate with those due to the interaction of glacio-eustatic oscillations and coastal uplift (DRAMIS 1992).

Holocene fluvial terraces (4 to 10 m above the valley floor) mostly reflect the dismantling of the more ancient alluvial deposits and the hillslope erosion induced by human impact (GENTILI & PAMBIANCHI 1987; CILLA et al. 1996; COLTORTI 1997). These deposits consist of sands and conglomerates with numerous intercalations of silt and clay near the river mouths. Locally, the incision exceeded the upper Pleistocene terrace reaching the underlying clayey bedrock (COLTORTI et al. 1991).

3. Recent evolution of the Adriatic fluvial-coastal systems

The effects of human activities on river erosion have been particularly strong since the second decade of the XX century. Direct measures carried out around the'70s and the use of historical maps (available since the end of the XIX century) and aerial photographs of different periods (since 1950), carefully georeferenced to be compared at a detailed scale, allowed the quantification of fluvial erosion-sedimentation processes (tab.1) in the study area and, in particular, of their effects on the river mouths (tab.2). However, given the purpose of this work, great attention has been focused on the variations contemporary or following the in-stream gravel mining practices, that reached their maximum between 1960 and 1975.

At the beginning of the XX century the rural landscape underwent deep modifications: deforestation (COLTORTI et al. 1995), development of agricultural practices and, in general, of hydraulic-forestry remedial works aiming at soil conservations. On the other hand, interventions for water regulation on the valley floors, that altered the shape and reduced the width of the river channels, allowed the cultivation of almost all the floodplains (CONTI et al. 1983). These processes continued up to the late 1950s, when remedial works on river banks and water regulation practices became more and more widespread. The overall result was a decrease of sediment supply to the rivers and, in correspondence to the narrowing of the thalwegs, an increase in flow velocity resulting in higher erosion capacity. However, until the end of the '50s, the effects of these processes have been relatively modest (BUCCOLINI & GENTILI 1986; MATERAZZI et al. 2010). The same processes have been observed also elsewhere in many Mediterranean basins where, before the ’50s, river incision due to human activities was a relatively localized and quite modest phenomenon. Cases of river bed incision were limited to segments of only a few kilometers in length, affected by steepening of the longitudinal profile in response to poorly executed hydraulic remedial works (BRAVARD et al. 1997). During the same period, in correspondence of the river mouths, the process of building of the delta apparatus, almost continuous since the Middle Ages (CONTI et al. 1983; COLTORTI et al. 1991), suffered a sharp trend reversal with phenomena of generalized withdrawal, sometimes rather intense (tab.2).

The situation changed rapidly in the early '60s when, in the mid-terminal stretches of the Adriatic rivers, in-stream mining practices became considerable (fig.2). In tab.1 are shown the main characteristics of the rivers investigated, the quantities quarried and the total duration of these practices (REGIONE MARCHE, 1976a and b) which have been forbidden (since 1972, following the approval of a national law on the prohibition of mining along the river beds. The consequences of these practices have been remarkable and were not limited to the original mining site but reached far upstream and downstream. The phases of the erosion processes are shown in fig.3. The mining practices initially created depressions in the river bed (fig.3a), which were filled by the coarse material of the ordinary bed load (fig.3b). As in the case of the dams or in general in the presence of transversal works along the water courses, the river velocity increased because of the lower bed load. The consequent strong fluvial incision involved the residues of upper Pleistocene and Holocene alluvial deposits and, locally, also the Pliocene-Pleistocene clay bedrock beneath (fig.3c). Soon after this, when gravel mining deepened the channel, less floodwaters were forced into the flood plain because the channel held more water. The combination of all these effects increased the water speed and were felt immediately downstream from the mined area, but as the erosion extended further downstream, the same impacts were repeated and the erosion became self-sustaining (fig.3c). Upstream impacts also occurred in the form of knickpoint erosion (MELTON 2009). This happens when river waters flow from the natural unmined stream into the deepened stream where the gravel was removed. At the point where the natural streambed changes to the mined area, the water speed increases causing an enhancement of the erosion and the incision of the channel (fig.2 and 3d). This process too was self-perpetuating and proceeded upstream under its own power. The strong fluvial incision, evaluated by the authors after direct measures and oral testimonies (tab.2), caused also heavy damage to built-up works (bridges, groins, levees) along the river beds (fig.4).

The effects of these processes are also recorded at the river mouths where, in the period 1978-1988, but sometimes also later, the generalized withdrawal of the first half of the XIX century suffered a strong decrease up to stability or local advancing phenomena, because of the temporary increase of bed load. Along some river beds these phenomena are not noticeable because of the presence of harbors and/or existing embankments: the latter did not allow the mining in the river bed that were instead made ?in neighboring areas. In addition, any solid load that reached the mouth was sometimes not sufficient to counteract marine erosion. A generalized strong retreat instead resumed after the 80s (tab.1), when the sediment delivery to the sea decreased drastically with the incision of river beds in the underlying clay bedrock (BUCCOLINI & GENTILI, 1986; BUCCOLINI & TIBERIO, 2001).

Less clear and difficult to read is the evolution of the mouths since the late ‘90s onwards, when human activities (marine erosion protection works and/or beach replenishments) mitigated or even canceled the processes active in previous decades.

4. Quantification of the effects of quarrying activities: an empirical approach

4.1 Methodology

A simple empirical approach, using two fluvial parameters (mean annual fluvial discharge and mean slope of the river channel), the amount of material quarried from the main Marchean rivers during the 1960-1975 period and the magnitude of the resulting fluvial incision in the following decades (tab.2), has been attempted in order to establish a possible relationship between the fluvial erosion capacity consequent to quarrying and the fluvial incision itself.

In fact, previous attempts to establish a direct correlation between those parameters (both as a total and as a rate) did not provide significant results to date (COLTORTI et al. 1995: MARCHETTI 2002).

Basic assumptions for the application of the following relations are: 1. a direct relationship among geometry, discharge and erosive capacity of a river; 2. a direct relationship between quarried material and erosive capacity; 3. considering the total amount of quarried material and not the quarrying rate.

LEOPOLD et al. (1964) introduced the *Total Stream Power per unit channel length* (Ω, N/s) for estimate the energy dissipation on a sector of the river:

$$\Omega = \gamma QS$$

where γ is the specific weight of water (N/m^3), Q is the fluvial discharge (m^3/s), S is the energy slope (dimensionless). If we consider $\gamma = 1$, the formula becomes

$$\Omega = QS.$$

Applying this formula to the whole river sector analyzed and considering the *Mean Annual Fluvial Discharge* (Q_m, N/s) and the *Mean Slope of the River Channel* (S_m, dimensionless) we obtain the *Mean Stream Power* (Ω_m) in the whole river

$$\Omega_m = Q_m S_m.$$

In order to consider the total quarried material that facilitates the capacity of river erosion we defined a new parameter, named *Global Fluvial Power Index* (Ω_G):

$$\Omega_G = \Omega_m Q_u$$

where Q_u is the total quarried material (m^3).

4.2 Data analysis and discussion

Plotting on a XY graph the data concerning the Ω_G and the *Fluvial incision* values (Fi) of the main Marchean rivers and interpolating them (fig.5, fine black curve), we obtained an exponential relationship that has a highly significant coefficient of determination (R^2=0.72). A comparable result (R^2=0.63) has been obtained integrating the above data with those (marked by the X symbol) regarding other four rivers (tab.1): two in northern Italy (Brenta and Tagliamento rivers, RINALDI et al. 2005), one in France (Darc River, BRAVARD et al. 1997) and one in Poland (Wisloka River, RINALDI et al. 2005). The bolt interpolation curve (fig.5) refers to all values.

This result confirms the correctness of the parameters used in the analysis and in particular the close correlation between river discharge, slope, and total amounts of quarried material; on the other hand, parameters such as the duration of the mining practices and, in general, the size of the river catchments seem less significant. Therefore we propose the following relation to evaluate the magnitude of *Fluvial incision* (Fi)

$$Fi = 4.7\ \Omega_G^{\ 0.14}$$

This relation is quite simple and easy to apply in terms of calculation and number of used data. However, considering that the relation has been verified so far only on 15 river basins, careful tests in different environments are still needed.

5. Conclusions

The present paper, through the analysis of several river basins of the Adriatic central Italy, evidenced how the fluvial-coastal system in this sector (as in other Mediterranean regions) has been characterized, since the beginning of the XX century, by phases of prevailing erosion and deposition strongly connected to human influence. These phenomena have been particularly relevant after 50’s when erosive processes occurred, essentially as a consequence of in stream mining activities along the river beds.

Because of the lack of quantitative approaches which take in account the effects of such practices on river channel processes, a simple empirical relation, aiming at correlate fluvial erosion capacity consequent to quarrying activities and fluvial incision, has been attempted. The encouraging results, even though verified so far only on few situations and spurring to further studies in different environments, provide an important contribution to the understanding of short and long-term responses of the hydrographic systems to human activities. This issue has become again topical after the flood events that have devastated the Italian territory in recent years; maintenance problems of the main rivers and major tributaries have pushed regional and local administrations towards often thoughtless interventions of cleanup and removal of materials from river beds, with consequent erosion processes of the river banks and beds.

A careful consideration is therefore needed considering the Directives 2000/60/EC and 2007/60/EC of the European Commission, which establish, respectively, a legislative framework for Community action in the matter of waters and for flood risk assessment and management. More in particular, the Directive 2000/60/EC reiterates, both in the statement and in the art. 3 and 4, the need to operate in an integrated manner at the scale of the river basin, in order to protect the ecological status of the water body; the art. 7-8-9 of the Directive 2007/60/EC, on the other hand, promote actions and interventions aimed at reducing, in the European Community, the negative consequences for human health, environment, cultural heritage and economic activities associated with floods. This latter has been subsequently transposed by the Italian Government that, in the law 152/2006 and law 49/2010, introduced, among other instructions, the concept of "Hydrographic District" and a set of guidelines for the proper management of the river beds.

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Figure captions

Fig. 1 Main geological features of the study area

Tab. 1 Main fluvial parameters, mining practices data of the rivers investigated and data used in the empirical formula for determining the *Fluvial incision* (Fi).

Fig. 2 In-stream gravel mines and erosion processes recognized along the middle-final stretches of the Marchean rivers

Fig. 3 Stages of channel evolution consequent to in-stream gravel mining (a, b, c, d): for the explanation see the text

Tab. 2 River mouth variation along the most important rivers of the Adriatic central Italy.

Fig. 4 Examples of channel incision along Adriatic rivers: a) along the Chienti River (1m over less than 5 years); strong fluvial incision affecting a bridge along the Potenza River b) and a stretch of pipeline along the Aso River c); d) fluvial incision in the mid-portion of the Tenna River: the downcutting at the base of the check dam shows values of about 8m over less than 10 years

Fig. 5 X-Y graph showing the relationship between *Fluvial incision* (Fi) and *Global Fluvial Power Index* (Ω_G) for the rivers listed in tab.1.

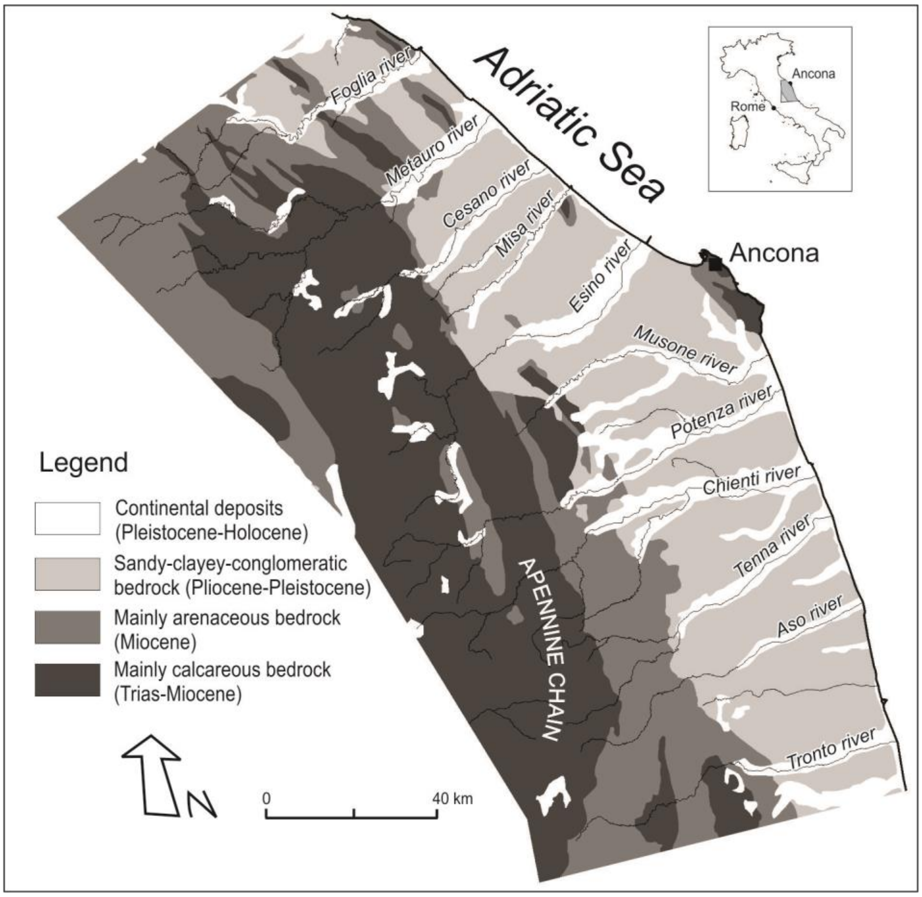
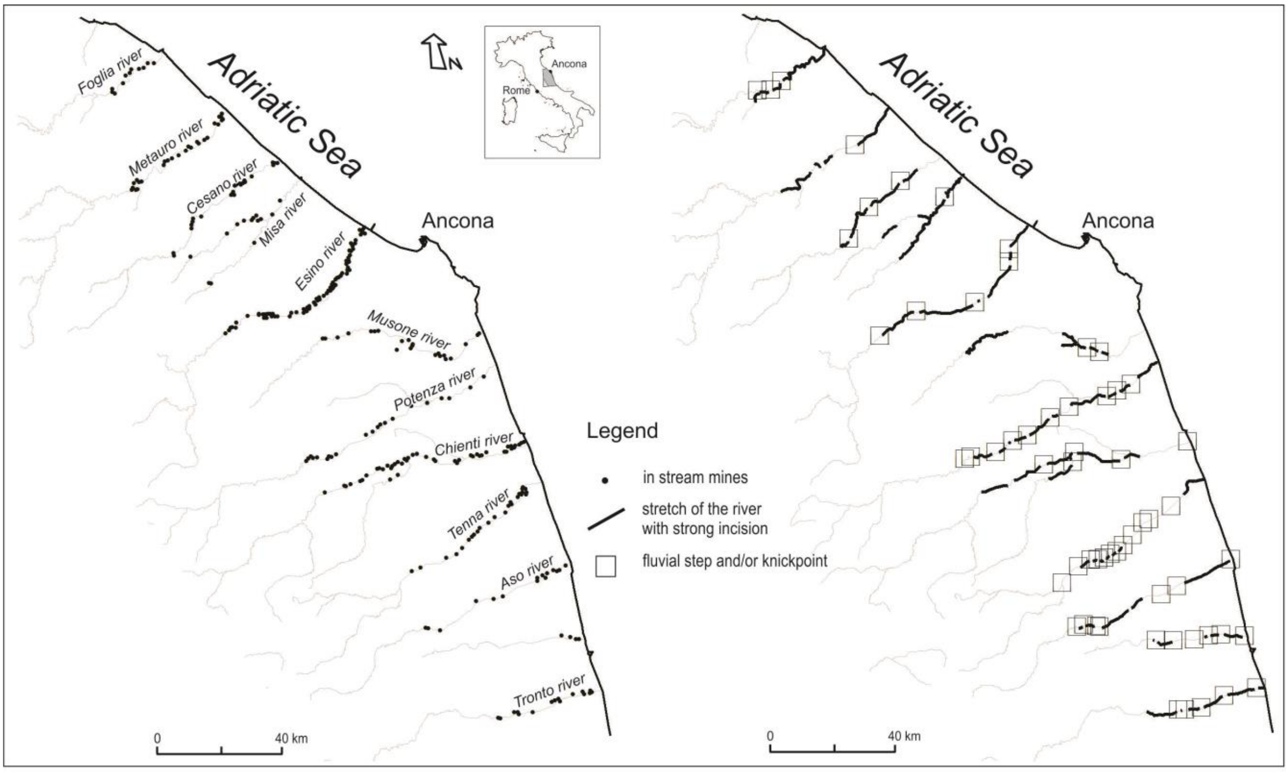

Adriatic Sea
Ancona
Rome
Foglia river
Metauro river
Cesano river
Misa river
Esino river
Musone river
Potenza river
Chienti river
Tenna river
Aso river
Tronto river
APENNINE CHAIN
Legend
Continental deposits
(Pleistocene-Holocene)
Sandy-clayey-conglomeratic
bedrock (Pliocene-Pleistocene)
Mainly arenaceous bedrock
(Miocene)
Mainly calcareous bedrock
(Trias-Miocene)
N
0
40 km

Fig.1


Adriatic Sea
Ancona
Rome
Foglia river
Metauro river
Cesano river
Misa river
Esino river
Musone river
Potenza river
Chienti river
Tenna river
Aso river
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in stream mines
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with strong incision
fluvial step and/or knickpoint
N
0
40 km

Fig. 2

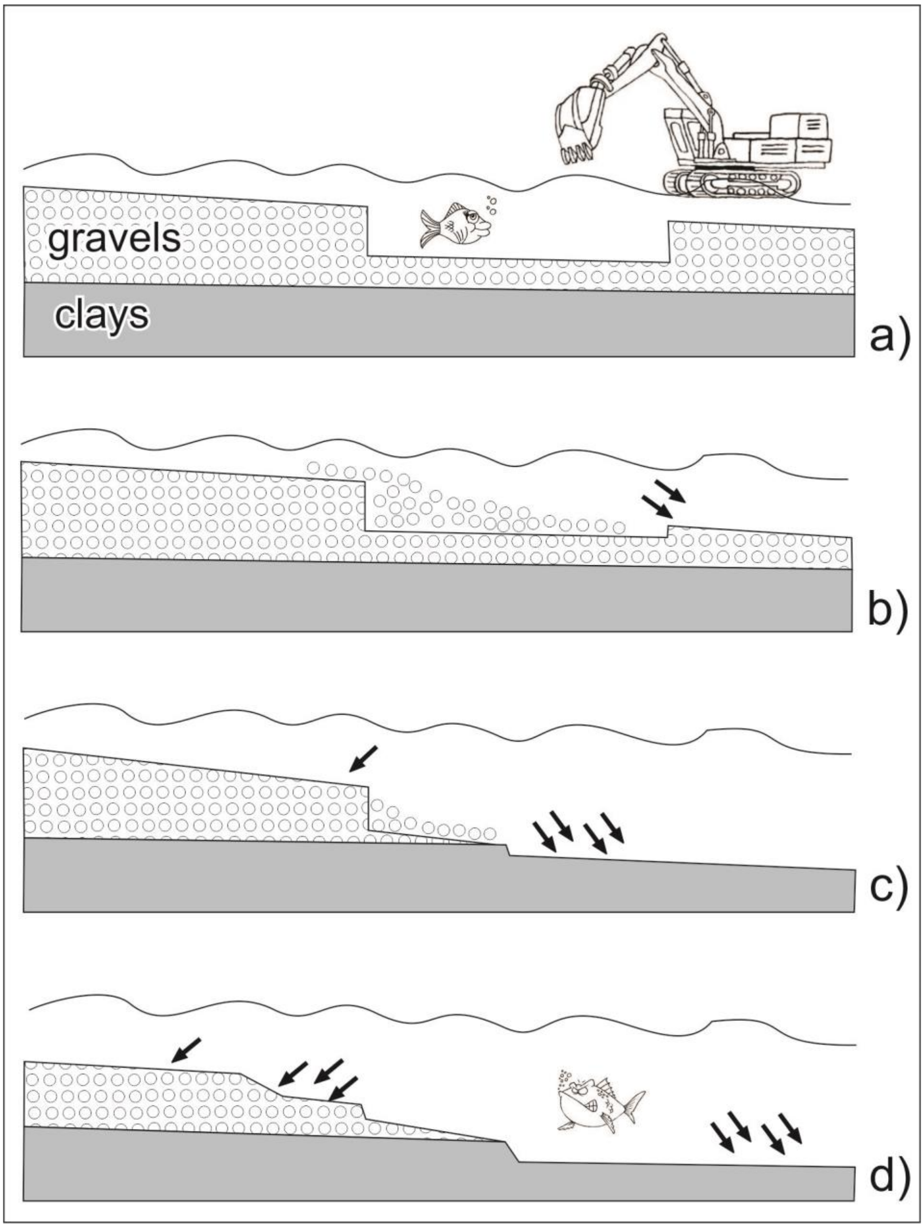


Fig. 3

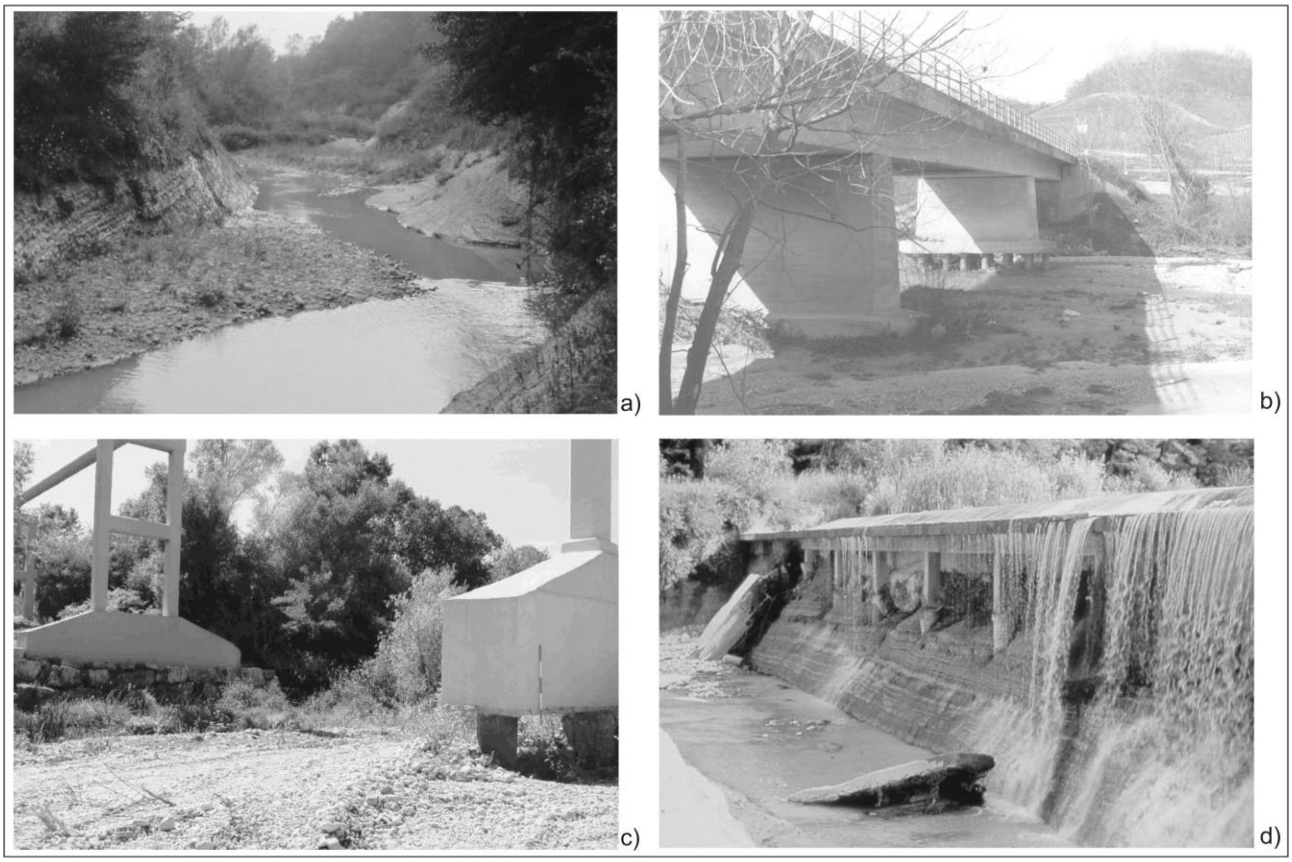


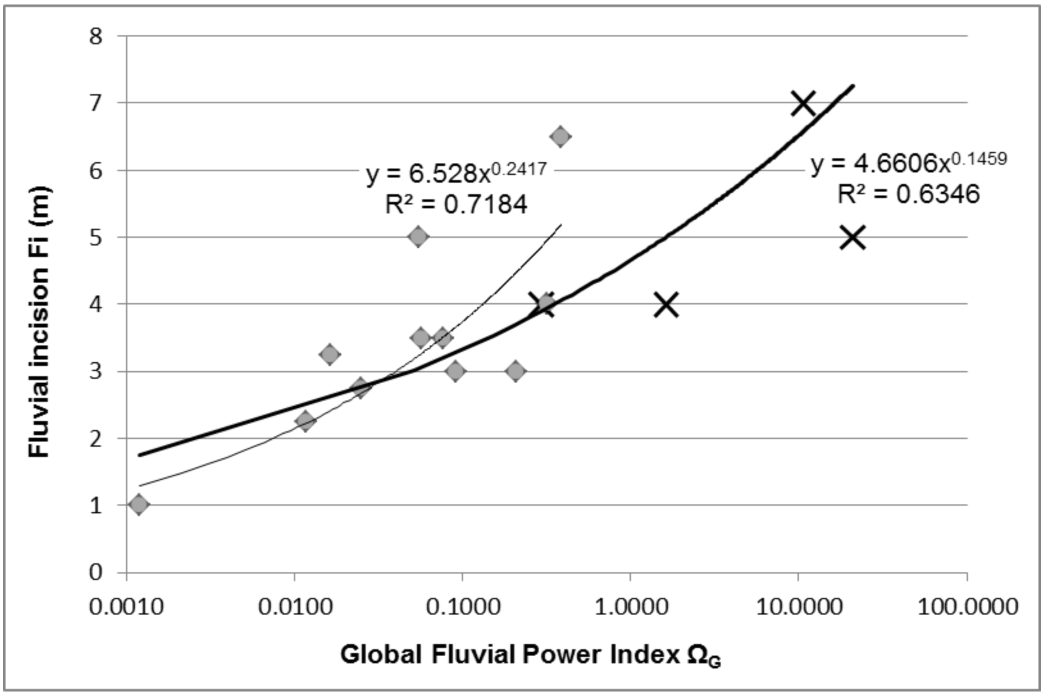
Fig. 4

Hydrographic basin	Location	Area (sqkm)	Fluvial parameters		Mean fluvial discharge (m^3/s) **Q_m**	Quarrying duration (yrs)	Quarried material ($m^3 \times 10^6$) **Qu**	Fluvial deepening (m) **Fd**	Mean stream power (Q_m x S_m) **Ω_m**	Global Fluvial Power Index (Ω_m x Q_u) **Ω_G**
			Lenght (m)	Mean slope **S_m**						
Foglia	Central Italy	701	71500	0.002	19.06	10	2	3.5	0.04	0.0762
Metauro	Central Italy	1389	94000	0.003	43.13	10	3	6.5	0.13	0.3882
Cesano	Central Italy	412	56500	0.005	11.78	3	0.2	2.25	0.06	0.0118
Misa	Central Italy	376	44000	0.004	10.03	5	0.03	1	0.04	0.0012
Esino	Central Italy	1148	77500	0.003	34.78	6	2	3	0.10	0.2087
Musone	Central Italy	643	65000	0.002	16.26	10	0.5	3.25	0.03	0.0163
Potenza	Central Italy	773	88000	0.003	21.58	7	1.4	3	0.06	0.0906
Chienti	Central Italy	1294	91000	0.003	39.33	10	2.7	4	0.12	0.3186
Tenna	Central Italy	484	69000	0.005	13.80	7	0.8	5	0.07	0.0552
Aso	Central Italy	280	71500	0.008	7.81	8	0.4	2.75	0.06	0.0250
Tronto	Central Italy	1192	97500	0.002	35.40	7	0.8	3.5	0.07	0.0566
Brenta	**Northern Italy**	**1567**	**174000**	**0.005**	**71.00**	**30**	**30**	**7**	**0.36**	**10.6500**
Tagliamento	**Northern Italy**	**2580**	**178000**	**0.008**	**109.00**	**21**	**24**	**5**	**0.87**	**20.9280**
Drac	**France**	**3350**	**130000**	**0.004**	**58**	**12**	**7**	**4**	**0.232**	**1.6240**
Wisloka	**Poland**	**4110**	**164000**	**0.004**	**35.00**	**9**	**2.1**	**4**	**0.14**	**0.2940**

Tab. 1

River	**River mouth advance (+) or withdrawal (-)**							
	1892-1954 m/yr	1954-1978 m/yr	1978-1988 m/yr	1988-1994/98 m/yr	1994/98-2000 m/yr	2000-2006 m/yr	2006-2010 m/yr	**1892-2010 m/yr**
Foglia	-2.8	*n.d.*	*n.d.*	*n.d*	*n.d*	*n.d*	*n.d*	-1.47
Metauro	-2.5	-3.1	2.5	-3.5	0	5	-8.8	-2.01
Cesano	-0.3	-2	-2.9	1.5	0	1.6	1.25	-0.58
Misa	-0.6	*n.d*	*n.d*	*n.d*	*n.d*	*n.d*	*n.d*	-0.31
Esino	-2.1	*n.d*	*n.d*	*n.d*	*n.d*	*n.d*	*n.d*	-1.1
Musone	-0.9	-2.39		-7.1	-0.6	1.2	-2	-1.67
Potenza	-0.4	3.1	-1.2	-1.5	0	-3.3	6	-0.82
Chienti	-2.9	4.1	-5.2	-1.25	-0.8	-1.1	-1	-1.33
Tenna	-1.9	4.9	-4.5	-1.75	0	-1.9	2.25	-0.52
Aso	-2.1	-0.43	-1.1	*n.d*	*n.d*	*n.d*	*n.d*	-1.28
Tronto	-7.1	-0.4	-3.91	-3.75	0	-4.2	-4	-4.74

Tab. 2



8
7
6
5
4
3
2
1
0
Fluvial incision Fi (m)
y = 6.528x^0.2417
R² = 0.7184
y = 4.6606x^0.1459
R² = 0.6346
0.0010
0.0100
0.1000
1.0000
10.0000
100.0000
Global Fluvial Power Index Ω_G

Fig. 5