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SEDIMENT MINING IN ALLUVIAL CHANNELS: PHYSICAL EFFECTS AND MANAGEMENT PERSPECTIVES

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ABSTRACT

Based on a review of a number of documented case studies from various countries and a detailed analysis of sediment exploitation from five rivers in Italy and Poland, we discuss alluvial river response to extensive sediment mining. A sediment deficit caused by in-stream mining typically induces upstream- and downstream-progressing river incision, lateral channel instability and bed armouring. The resultant incision alters the frequency of floodplain inundation along the river courses, lowers valley-floor water tables and frequently leads to destruction of bridges and channelization structures. Mining also results in the loss or impoverishment of aquatic and riparian habitats. In the rivers of Italy and southern Poland studied, where mining coincided with other human activities that reduce sediment delivery to the channels, deep river downcutting, changes in channel pattern and, in one case, transformation from alluvial to bedrock boundary conditions were recorded over recent decades.

The type and magnitude of channel response to sediment mining depend mainly on the ratio between extraction and sediment replenishment rates. The effects of mining will be especially severe and difficult to reverse: (i) where material is extracted at a rate greatly exceeding the replenishment rate; (ii) in single-thread rivers, that are generally associated with relatively low rates of catchment sediment supply; (iii) in channelized reaches; (iv) where rivers are underlain by a thin cover of alluvium over bedrock; and (v) where mining coincides with other human activities that reduce upstream sediment delivery. With a large number of detrimental effects of instream mining, the practice should be prohibited in most rivers except aggrading ones.

KEY WORDS: sediment mining; alluvial rivers; channel incision; river management

INTRODUCTION

Alluvial rivers have historically been an attractive source of sediment for a variety of industrial uses. Commercial sediment extraction from alluvial rivers is a global phenomenon, particularly intense in countries subject to rapid urban and industrial growth over recent decades and lacking alternative sediment sources (Sear and Archer, 1998; Kondolf, 1994a, 1994b).

Sediment is also removed from channels to restore or maintain flood capacity. This practice can be an effective tool for flood control and channel stability in rapidly aggrading rivers, but it can have dramatic effects in incising rivers. In fact, the latter are much more common in Europe and North America as a consequence of many other human factors reducing sediment supply (Kondolf, 1994a, Wyżga, 2001a).

Because of limited and ineffective regulatory control (Collins and Dunne, 1990; Kondolf, 1994b), sediment exploitation for commercial and industrial purposes has produced many detrimental effects, including upstream and downstream channel incision and its consequences (damage to bridges and other structures), lateral channel instability, water table lowering, loss of riparian and aquatic habitats, and several other ecological and environmental impacts.

Poor documentation of the adverse effects of sediment mining in the geomorphological and engineering literature partly explains why their potential occurrence was commonly neglected by river managers in the past.

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Extensive reviews, mainly focused on rivers of the USA, began to be published from the 1990s (Collins and Dunne, 1990; Kondolf, 1994a, 1997), and specific recommendations for sediment management have been more recently proposed for the Fraser River (Canada) (Church *et al*., 2001). Although in some countries (e.g. France, Italy, Poland) bed material extraction has been limited or formally prohibited over recent decades, the demand for sediment exploitation is still continuing, and permissions are often granted under the motivation of flood control. Moreover, in some countries (e.g. Poland), illegal extraction of bed material from mountain stream channels is a frequent practice (Wyżga, 2001a, Radecki-Pawlik, 2002). Therefore, management of sediment sources and regulation of mining activity are still important issues. In order to improve present and future management of the sediment resource, it is important to gain a better knowledge of the geomorphic effects of sediment mining and to extend documented cases of the types and amount of mining-related channel adjustments to a greater variety of environments.

The aims of this paper are: (a) to make a general review of impacts of sediment mining on alluvial rivers; (b) to illustrate some cases of intense in-stream mining and its effects in selected areas of Italy and Poland that are representative of a relatively wide range of situations; (c) to discuss the role of different factors influencing the type and magnitude of channel response; (d) to draw some general conclusions in terms of future strategies for managing sediment mining.

ADVANTAGES AND TYPES OF SEDIMENT MINING

Alluvial channels have historically been an attractive source of sand and gravel for a variety of construction activities. There are several advantages for the aggregate operators in using river sediment (Kondolf, 1994a), such as: (a) the material is already granulated, rounded, well-sorted, and generally clean (lacking cement and weak materials, and relatively free of interstitial fine sediment); (b) the source of material is generally close to destination or to the markets for the product, reducing transportation costs; (c) active channel sediments can be easily quarried (deep quarrying is not necessary), require little processing, and are periodically replaced from upstream during high flow events.

The environmental costs of sediments extracted from active channels are generally not taken into account in cost–benefit analysis, making this source much more profitable compared to other alternatives (such as dry terrace mines, quarries, reservoir deltas) (Kondolf, 1994a). For the above reasons, commercial sediment extraction from alluvial rivers is a global phenomenon, particularly widespread in industrialized countries.

Three types of in-stream sediment mining can be distinguished (Kondolf, 1994a): (a) dry-pit mining, carried out on dry ephemeral stream channels with conventional bulldozers, scrapers and loaders; (b) wet-pit mining, below the water level on perennial streams, requiring the use of a dragline or a dredge; (c) bar skimming, consisting of scraping off the top layer (of variable thickness) from a gravel bar without excavating below the low water level.

Alluvial sediments can be also mined from adjacent floodplains and older terrace deposits. In many cases, the pits are constructed adjacent to the active channel, separated only by a small levee.

EFFECTS OF SEDIMENT MINING ON CHANNEL MORPHOLOGY AND ENVIRONMENT

Sediment mining produces a large variety of physical, ecological, and environmental effects. The main physical effects are listed in Table I and briefly described as follows. In the following description some of the ecological and environmental impacts are also cited, although the list is not exhaustive.

Morphological effects

(1) Upstream incision. The excavation steepens the slope of the channel bed upstream of the extraction hole, creating a headcut that will tend to move for kilometres upstream (headcutting). The bed-level lowering of the main channel also lowers the base level of tributaries, increasing their slope and triggering their rapid erosion.

(2) Downstream incision. Pit excavation can also induce incision downstream, particularly if the sediment mining is intense and prolonged. In fact, the excavation creates a trap for sediment, interrupting the sediment transport in the reach, inducing a sediment deficit and the resultant excess of energy downstream.

Table I. Summary of the possible physical effects of sediment mining on alluvial channels

Main types of physical effects	Main references
Upstream incision (headcutting along the main river and tributaries)	Lane (1947), Sato (1971, 1975), Kira (1972), Scott (1973), Forshage and Carter (1973), Bull and Scott (1974), Prudhomme (1975), Simons *et al*. (1979), Lagasse *et al*. (1980), Galay (1983), Chang (1988), Collins and Dunne (1989, 1990), Erskine (1990), Kondolf (1994a, 1994b, 1997), Sandecki and Avila (1997), Sear and Archer (1998), Surian and Rinaldi (2003), Marston *et al*. (2003)
Downstream incision	Galay (1983), Brookes (1988), Chang (1988), Erskine (1990), Lee *et al*. (1993); Sandecki and Avila (1997), Rinaldi and Simon (1998), Rinaldi (2003)
Impacts to infrastructures (bridges, aqueducts, sewer lines, gas conduits)	Osuch (1968), Cullen and Hughes (1975), Maraga and Mortara (1981), Collins and Dunne (1990), Kondolf (1994b, 1997), Erskine (1997), Sandecki and Avila (1997), Piégay *et al*. (1997), Agnelli *et al*. (1998), Rinaldi and Simon (1998), Erskine and Green (2000), Marston *et al*. (2003), Uribelarrea *et al*. (2003)
Channel instability (lateral changes, changes in channel width and morphology)	Chang (1988), Collins and Dunne (1990), Petit *et al*. (1996), Bravard *et al*. (1997), Erskine (1997), Sear and Archer (1998), Erskine and Green (2000), Surian and Rinaldi (2003), Rinaldi (2003), Wyżga (2001b)
Bed armouring	Simons and Lagasse (1976)
Channel instability induced by gravel bar skimming	Collins and Dunne (1990), Kondolf (1994a)
Channel capture by off-channel pit and reactivation of inactive channels	Scott (1973), Bull and Scott (1974), Dunne and Leopold (1978), Collins and Dunne (1990), Kondolf (1997)
Effects on frequency of inundation	Collins and Dunne (1990), Augustowski (1968), Wyżga (1997, 2001b)
Water table lowering	Lach (1975), Collins and Dunne (1990), Hatva (1994), Mas-Pla *et al*. (1999)
Changes in tidal hydrodynamics	Erskine (1990)
Sediment deficit to coastal zone	Tagliavini (1978), Gaillot and Piégay (1999)

(3) Lateral channel instability. Incision is often accompanied by lateral instability and changes in channel width, triggering bank erosion and channel migration in formerly stable reaches.

(4) Bed armouring. Sediment deficit caused by instream mining leads to the selective outwashing of finer grains from bed material and the development of bed armour.

(5) Effects of gravel bar skimming. Similar to pit excavation, gravel bar skimming alters the continuity of sediment transport and may induce downstream incision and lateral instability of the channel, although the volumes removed are typically smaller than those removed for pit mining (Kondolf, 1994a). Skimming also removes the coarser surface layer of sediment that occurs on many natural rivers, favouring bed erosion and increasing bedload transport.

(6) Effects of floodplain pit mining and reactivation of inactive channels. When pits are constructed near the river and separated only by a strip of land (typically along inactive channels), an avulsion or a more gradual channel migration may cause the pits to be captured during floods. The former off-channel pit is then converted into an in-channel pit, and the effects typical of instream mining can be expected. Another important concern of floodplain mining is that wet pits typically intersect the water table, and therefore constitute a preferential path of groundwater contamination and pollution.

(7) Impacts on infrastructures. As a result of bed degradation, bridges and channelization structures can be undermined, and pipelines or other structures buried under river beds can be exposed and damaged.

(8) Effects on coastal zones. Downstream sediment deficit can also have adverse effects on the coastal zones, triggering or accentuating beach erosion.

Hydrological effects

(9) Water table lowering. Channel incision may induce a lowering of the water table hydrologically connected to the river, reducing the storage capacity of the alluvial aquifer.

(10) Effects on frequency of inundation. The frequency and depth of inundation are typically reduced by the increased conveyance capacity due to the removal of sediment and by the induced channel bed lowering. However, the benefits in terms of reduced hazard are not always effective, because: (i) the reduced channel slope generally resulting from downstream incision decreases flow velocities and may in part counterbalance the increased cross-section area; and (ii) the water surface profile may be controlled by natural (i.e. sea level) or artificial fixed points in the longitudinal profile so that the effects of channel-bed lowering are negligible during intense flood events. Moreover, as water retention on the floodplain is reduced or even eliminated following channel incision, this decreases attenuation of flood waves passing the incised reach; as a result, increased flood magnitudes are recorded downstream of the reach.

(11) Changes in tidal hydrodynamics within estuaries. Sediment deficit, caused by mining within an estuary or in the upstream river channel, can increase tidal penetration into the estuary, tidal range, and peak tidal discharges (Erskine, 1990).

Ecological and environmental effects

(12) Loss of riparian and aquatic habitats. In-stream mining destroys in-channel alluvial features (riffles, pools) important for enhancing habitats and their diversity. Bed coarsening and removal of gravel suitably sized for spawning are of particular concern on rivers supporting salmonids (salmon and trout) (Kondolf, 1994a; Cote *et al*., 1999). Destruction of islands and bars as well as the removal of large woody debris in the course of sediment extraction reduce morphological and hydraulic diversity of the river and lead to the loss of aquatic habitats (Erskine, 1997; Erskine and Green, 2000). Moreover, dredging river shallows removes the substratum for submerged and emerged macrophytes (Erskine, 1997). Water-table lowering can result in widespread loss of riparian vegetation, which in turn causes loss of wildlife habitats, destruction of local flora and fauna and loss of shade and cover to the channel (Girel and Doche, 1983). The abandonment of active floodplain by incision causes a loss of wet areas and related habitats.

(13) Other effects. Operation of mining can increase suspended sediment transport downstream, affecting benthic invertebrates and fish populations (Erskine, 1990, 1997). Dredging rivers impounded by weirs can increase water depths to the extent allowing development of persistent thermal and oxygen stratification of the water column during summer time (Erskine, 1997; Erskine and Green, 2000). The noise and traffic of a heavy industrial equipment can discourage wildlife along the riparian zone. Finally, creation of quarrying areas produces an aesthetic degradation of the fluvial landscape.

CASE STUDIES

In this section, selected case studies from Italy and southern Poland where in-stream sediment mining has been particularly intense are described in detail. Generally, among European rivers, it is difficult to select examples where mining has been the only type of human intervention. Sediment extraction from channels typically occurred there in combination with other types of disturbances (channelization, dams, land-use changes). Thus, the cases reported are useful to address the relative importance of mining compared to other types of interventions or disturbances.

Following these closely examined cases, other cases described in the literature are reported to allow a more complete overview and to make comparisons among effects of mining in different geomorphic contexts. Some of the cited cases represent situations where sediment mining has been the only, or certainly the most important, human disturbance and, therefore, they are suitable to illustrate the specific effects of mining.

Rivers of north-eastern and central Italy

A recent review of the effects of river engineering and management on Italian rivers (Surian and Rinaldi, 2003) has shown significant channel adjustments during the last 100 years, mainly incision and channel narrowing. Various types of human interventions have been indicated as their possible causes, but sediment mining is the most frequently cited cause.

Like most Italian rivers, the Tagliamento, the Brenta, and the Arno Rivers have been subjected to human disturbances with sediment mining being the main disturbance in recent decades. The Tagliamento and the Brenta Rivers drain the northeastern part of Italy, flowing from the Alps to the Adriatic Sea (Figure 1(A)). Their respective physiographic and hydrologic characteristics are as follows: drainage basin areas are 2580 km^2 and 1567 km^2; river lengths are 178 km and 174 km; precipitation is 2150 $\mathrm{mm\,yr}^{-1}$ and 1390 $\mathrm{mm\,yr}^{-1}$; mean annual discharges are 109 $\mathrm{m}^3\,\mathrm{s}^{-1}$ and 71 $\mathrm{m}^3\,\mathrm{s}^{-1}$. They are gravel-bed rivers with long reaches of a braided morphology. The Tagliamento has a braided morphology along more than half of its course, whereas the Brenta shows a braided pattern only in the piedmont plain.

Various human interventions have taken place in these two rivers during the last centuries (e.g. construction of levees, mainly in the 19th century, dams, etc.), but sediment mining has certainly had the greatest impact on their recent dynamics. In the Tagliamento River, gravel mining was particularly intense between the 1970s and the 1980s. Along some tens of kilometres of the river and its main tributaries more than 24 million cubic metres of sediments were extracted from 1970 to 1991 (Figure 1(B)). It is worth noting that this value is underestimated because it comes from official data, which commonly do not correspond to the actual volumes extracted, and because it does not include a reach of the river for which data were not available. Given that the annual sediment supply in the Tagliamento has been estimated at 1.3 million cubic metres (Autorità di Bacino dei fiumi dell'Alto Adriatico, 1998), sediment extraction rate was close to (or probably higher than) replenishment rate. In the Brenta River, sediment mining was particularly severe between the 1950s and the 1980s, and even more intense than in the Tagliamento. Though no complete records of the volumes of sediment mined are available, it can be estimated that some tens of millions of cubic metres were extracted along a relatively short reach (25–30 km) of the Brenta during that period. Sediments were extracted both within and outside the active channel. Dams have had little impact on the Tagliamento where only 3% of the whole drainage area lies upstream from dams, but they have had a more significant impact on the Brenta where a dam was constructed in 1954 about 30 km upstream of the upper end of the mining reach.

As a result of sediment mining, both rivers have experienced remarkable channel adjustments, particularly incision and narrowing, over recent decades. In the Tagliamento, which has a very wide braided belt, bed-level lowering has been of the order of 2–3 m (Figure 1(C)) and an average channel narrowing of 520 m has taken place (from 1200 to 680 m in the period 1954–1993) (Surian, 2005). In the Brenta, channel incision has amounted to up to 5 m in the braided reach and up to 7–8 m in the reach with single-thread morphology (Castiglioni and Pellegrini, 1981). In this river, incision and narrowing have also produced significant changes in the channel pattern, from braided to wandering but also from braided to single-thread. Figure 1(D) clearly shows not only such changes in channel configuration, but also the dramatic decrease in the area of exposed sediments (bars), and therefore in sediment supply to the river, that occurred between the 1950s and the 1990s.

Besides morphological effects on river channels, sediment mining in these two rivers has produced several effects on structures and environment. Impact on structures is well-documented in the Brenta River (for instance two bridges on this river failed in the 1970s), but also exists in the Tagliamento River. As regards environment, there has been a significant loss of groundwater resources due to channel incision and, along the Brenta River, an increase of pollution risk due to exposure of the water table in some mining pits (see Figure 1(D). Aquatic and riparian ecology were not significantly affected in the Tagliamento (Ward *et al*., 1999) but they might have been in the Brenta (Surian, 2005). Finally, channel adjustments have a significant effect on floods, since channel narrowing and incision cause a faster flood conveyance and, consequently, an increase of flood hazard in the downstream reaches (this is confirmed by hydraulic modelling of propagation of flood waves).

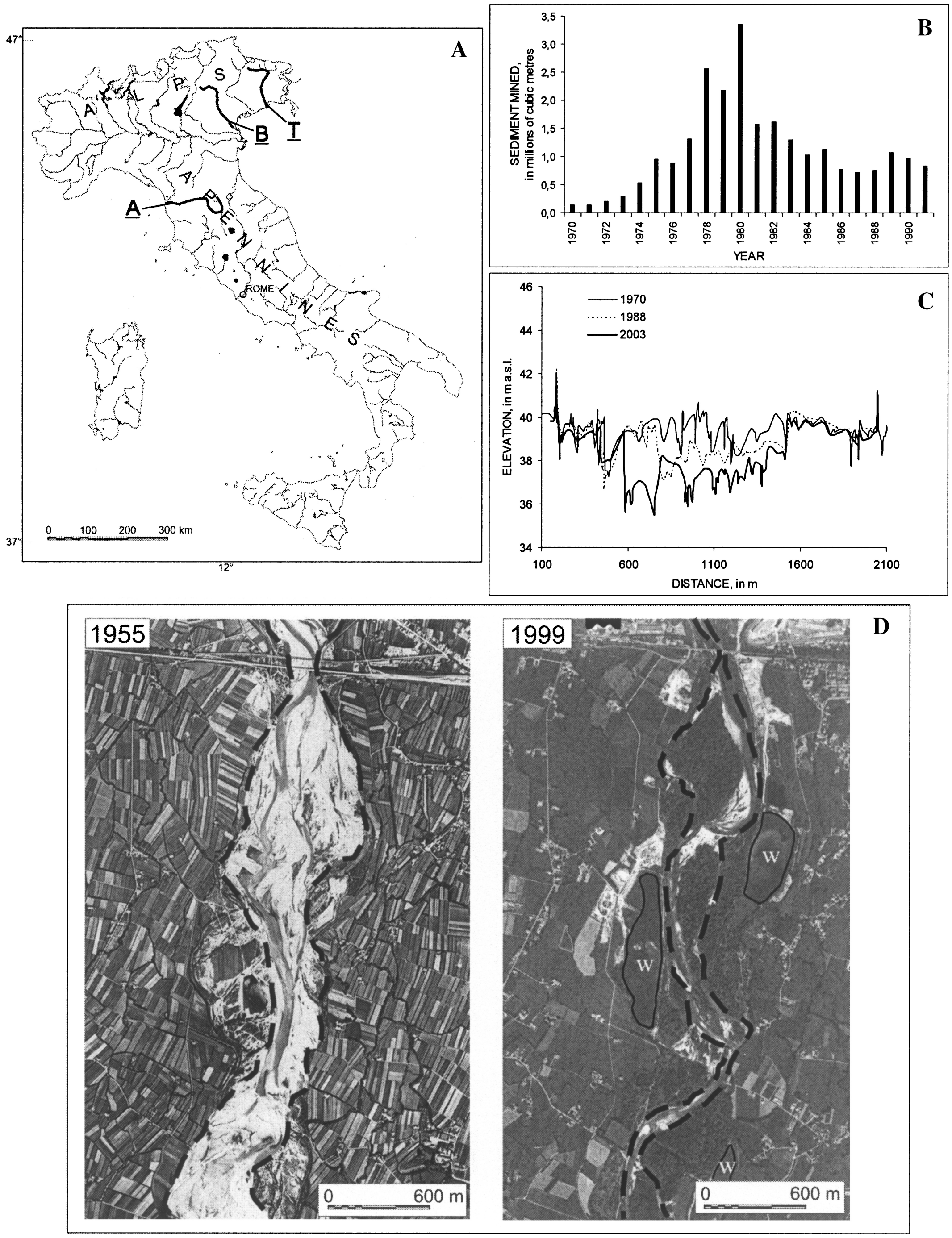

Figure 1. (A) Location map for the Tagliamento (T), the Brenta (B) and the Arno (A) Rivers. (B) Sediment mining along the Tagliamento River and its tributaries from 1970 to 1991. (C) Example of cross-section changes in the Tagliamento River (in the alluvial plain reach) between 1970 and 2003 as a result of the morphological adjustments induced by sediment mining along the reach. (D) Changes in channel configuration in the Brenta River between 1955 and 1999: incision and narrowing have produced changes from braided to wandering and from braided to single-thread. Active channel is pointed out by dashed lines; in the 1999 aerial photographs 'w' shows the mining pits where the water-table is exposed

The Arno River represents a well-documented case of a long history and complex combination of human disturbances and resulting channel adjustments (Billi and Rinaldi, 1997; Agnelli *et al*., 1998; Rinaldi and Simon, 1998). Its catchment has an area of about 8228 km^2; the river originates in the northern Apennines and outflows into the Tyrrhenian Sea after a course of about 245 km (Figure 2(A)). Mean annual discharge increases from 18.5 $\mathrm{m}^3\,\mathrm{s}^{-1}$ in the upper reach, to 97.4 $\mathrm{m}^3\,\mathrm{s}^{-1}$ in the coastal plain reach. Channel gradient ranges from about 0.005 to 0.001 $\mathrm{m\,m}^{-1}$ to minimum values of around 0.000 02 $\mathrm{m\,m}^{-1}$. Bed sediments are predominantly gravel; channel morphologies vary from sinuous with alternate bars in the upper reach to sinuous-meandering in the lower reach.

Notwithstanding the extensive channelization and straightening of most of the river, there is evidence that the Arno River fluvial system was characterized up to the mid-19th century by a prevailing depositional trend, with a general growth of the alluvial plains and delta progradation, related to the prevailing effects of land-use changes (deforestation) and a consequent increase in sediment supply (Billi and Rinaldi, 1997). Starting from the first decades of the 20th century, the channel bed started to degrade and the coastline started to erode as a consequence of a drastic reduction of sediment supply caused by the reafforestation of large upland areas.

During the 20th century, sediment mining has certainly represented the most relevant disturbance, although two dams were also built in 1957 along the upstream reach. River-bed sediment had been always exploited in past centuries but at a modest rate, which did not produce any significant effect on the prevailing depositional trend. At the beginning of the 20th century, the demand for river sediment for building material grew greatly following the modernization and the industrial development of the area. During the three decades after World War II, the volume of bed material extracted from the Arno River and its tributaries increased by several orders of magnitude as a consequence, initially, of the postwar reconstruction and, later, of the fast-growing industrialization and urbanization. The effects of such extensive sediment exploitation were soon evident and, at the beginning of the 1980s, local authorities found it necessary to halt the severe river bed degradation by prohibiting bed-material extraction.

As data on sediment volumes extracted from the channel are not available, an idea of the frequency and intensity of the exploitation can be obtained from the location of mining sites (Figure 2(A)), although they are not strictly referred to in-stream mining but often to points of extraction in the adjacent plain. Based on a comparison of topographic profiles from different years (starting from 1845 up to 1987), the amounts of bed-level lowering along the Arno River downstream from the two dams are shown in Figure 2(B).

Bed-level changes through time are best shown in Figure 2(C) for two representative cross-sections, where sufficient data were available (from cross-section data or specific gauge analysis). The first example is related to the reach of the Arno River (Lower Valdarno) characterized by the largest total incision in the region, while in the second case the river is characterized by a minor amount of incision, because it is a partially bedrock-controlled reach. As reported in a previous study (Rinaldi and Simon, 1998), two distinct phases of incision are distinguishable. A first minor degradational phase (end of the 19th century to first half of the 20th century) was the result of the changes at basin scale (construction of weirs along tributaries, reafforestation). This phase was followed by an abrupt acceleration of degradation, starting from the period 1945–1960 and extending to the beginning of the 1980s, with a significantly greater total incision. Data on annual maximum discharges, available since the 1920s, give little evidence of significant changes in magnitude or frequency of floods that could possibly explain the acceleration of channel incision observed in the second half of the 20th century. On the contrary, this second phase exactly coincides with the large increase in sediment mining after World War II.

As one of the main consequences of channel incision, several bridges along most of the river course have required onerous consolidation interventions during the last decades, and other bridges are still now in precarious stability conditions. The problem is particularly serious along the lower Valdarno and Pisa plain, the reaches with the highest bed incision: 9 bridges have required hard interventions of foundation consolidation and/or bed protection (rip-rap), and 5 weirs have been built to protect the bridges and to prevent bank failures along urbanized areas (Agnelli *et al*., 1998).

Rivers of southern Poland

In southern Poland, the alluvium of rivers draining the western Carpathians is the only available source of gravel. The Wisłoka and its tributary, the Ropa, are spectacular cases of the response of Carpathian rivers to the intense mining of channel sediments. These rivers drain the lowest part of the main Carpathian range in Poland, the Low

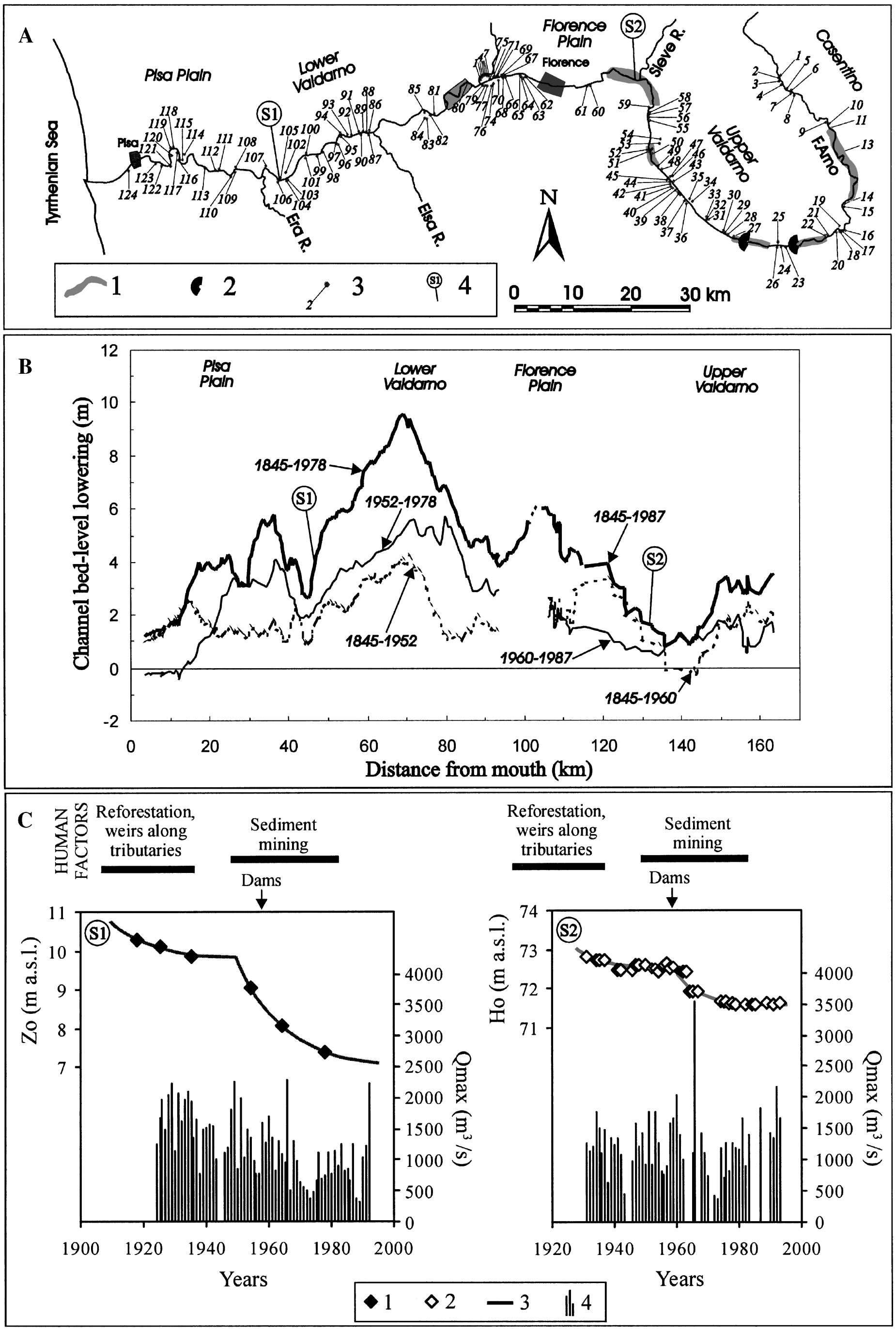

Figure 2. Bed-level adjustments along the Arno River (central Italy). (A) Location map for the Arno River system, with main alluvial reaches and the location of interventions (dams and mining sites) during the 20th century indicated. (1) Bedrock controlled reaches. (2) Dams. (3) Sites of sediment excavation from the channel bed and/or the adjacent alluvial plain. (4) Representative sections for trends of bed-level adjustments (shown in Figure 2(C)). (B) Channel bed-level lowering of the Arno River (moving averages) after 1845. (C) Trends of bed-level adjustments and flood record for two sections of the Arno River (location is shown in Figure 2(A)). (S1) Arno River in the Lower Valdarno reach.(S2) Arno River in the middle course (data obtained by specific gauge analysis). (1) Bed-elevation (Zo) by cross-section data; (2) river stage associated with the mean of annual minimum discharges (Ho) (by specific gauge analysis); (3) trend of bed-level adjustments; (4) annual peak flow (Q_{max}) (data of 1944 and 1945 are missing). Human disturbances: horizontal bars indicate the period of maximum human activity; the arrow indicates the year (1957) of construction of the two dams in the upper course of the Arno River

Beskid Mountains, with the highest point in their catchments at 938 m a.s.l. (Figure 3). Their relatively low channel gradients and low amounts of precipitation in the montane parts of both catchments (about 800–850 mm annually) result in relatively fine-grained composition of bed material, suitable for concrete production.

The Ropa River drains an area of 970 km^2 and its mean annual discharge at Topoliny, close to the river mouth (Figure 3), is 9.8 m^3 s^{-1}. In the foothill reach of the river, channelization works carried out in the early decades of the 20th century induced streambed degradation of about 0.4–0.5 m, followed by vertical channel stability since the early 1930s. The bed material of the river consisted of pebble gravel in this reach and formed conspicuous bars within the channel (Figure 4(A)). In-stream sediment mining was initiated in 1941 at Biecz (Figure 3) and after World War II gravel exploitation at the site was considerably enlarged, now comprising a section of the river a few kilometres long (Augustowski, 1968). The exploitation continued until the complete exhaustion of the gravel resources in the channel in the mid-1960s. In total, at least 1 million cubic metres of gravel were taken from the river channel between 1941 and 1966 and additional gravel was mined in pits on the valley floor (Augustowski, 1968). The significance of the in-stream mining to the river can be illustrated by noting that a 1 m thick layer of material would need to be removed from the 25 km-long section of the Ropa channel of 40 m width to provide such a volume of sediment if no bed material was supplied from upstream during that period.

The mining has had a dramatic influence on river morphology. The influence has been increased by the simultaneous reduction in sediment delivery to the river resulting from a considerable decrease in agricultural activity in the Low Beskid Mountains since the mid-1940s and the subsequent reafforestation of the area (Lach, 1975; Lach and Wyżga, 2002). At Biecz, the river incised by about 1.5 m and its channel was transformed into a bedrock one by the mid-1960s (Figure 4(A)) (Augustowski, 1968). Incision at the mining site must have induced upstream

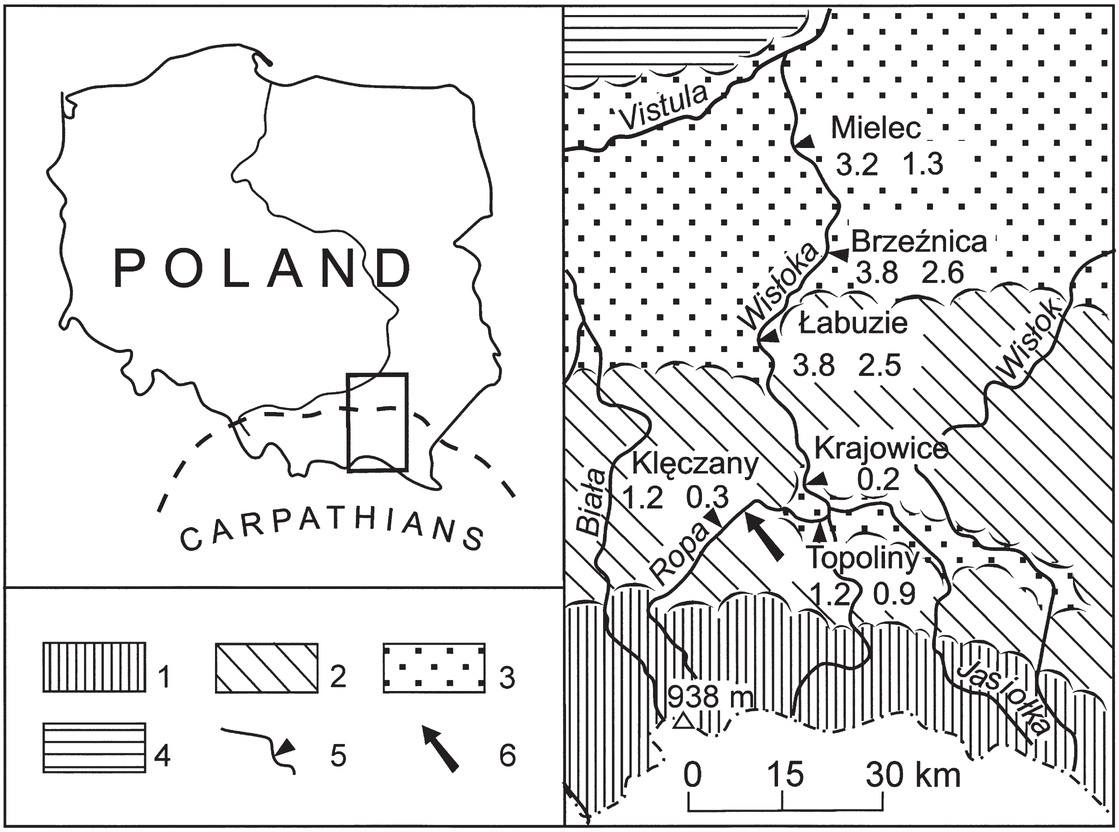

Figure 3. Location of the Ropa and Wisłoka Rivers on the background of physiogeographic regions of southern Poland and dimensions (in metres) of channel degradation of the rivers over the 20th century and in its second half (in brackets) inferred from the lowering of minimum annual water stage at gauging stations. 1, mountains of intermediate and low height; 2, foothills; 3, intramontane and submontane depressions; 4, uplands; 5, water-gauge stations; 6, location of the mining site in the Ropa River at Biecz

progressing degradation (see Galay, 1983; Kondolf, 1997) manifested in two degradation events that lowered the channel bed at the Klęczany gauging station, a few kilometres upstream (Figure 3), by about 0.7 m between 1941 and the mid-1970s (Figure 4(B)). These degradation events apparently reflected the retreat of two headcuts through the gauging section (see Wyżga, 1993). Since the mid-1970s, with the river incised to bedrock here, streambed degradation at the station has ceased. Moreover, sediment starvation below the place of exploitation has induced downstream progressing degradation (see Galay, 1983; Kondolf, 1997). At Topoliny, about 20 km downstream, slow incision lowered the channel bed by 0.5 m during the 1950s to 1970s (Figure 4(B)). Subsequently, with intense bed scouring initiated by the large flood of 1980, the channel bed degraded rapidly by about 0.4 m in the early 1980s and the river incised to bedrock. At the same time, a near-stable vertical position of the Wisłoka channel at Krajowice, a few kilometres downstream of the mouth of the Ropa, was observed over the second half of the 20th century (Figure 3). This shows that lowering of base level did not play a significant role in inducing the bed degradation at Topoliny and that the degradation must be attributed to the upstream-borne sediment deficit of the Ropa.

Incision of the Ropa has caused two important impacts on the river and valley hydrology. First, flood flows, which prior to 1941 inundated the valley floor, are now conveyed entirely within the deepened channel

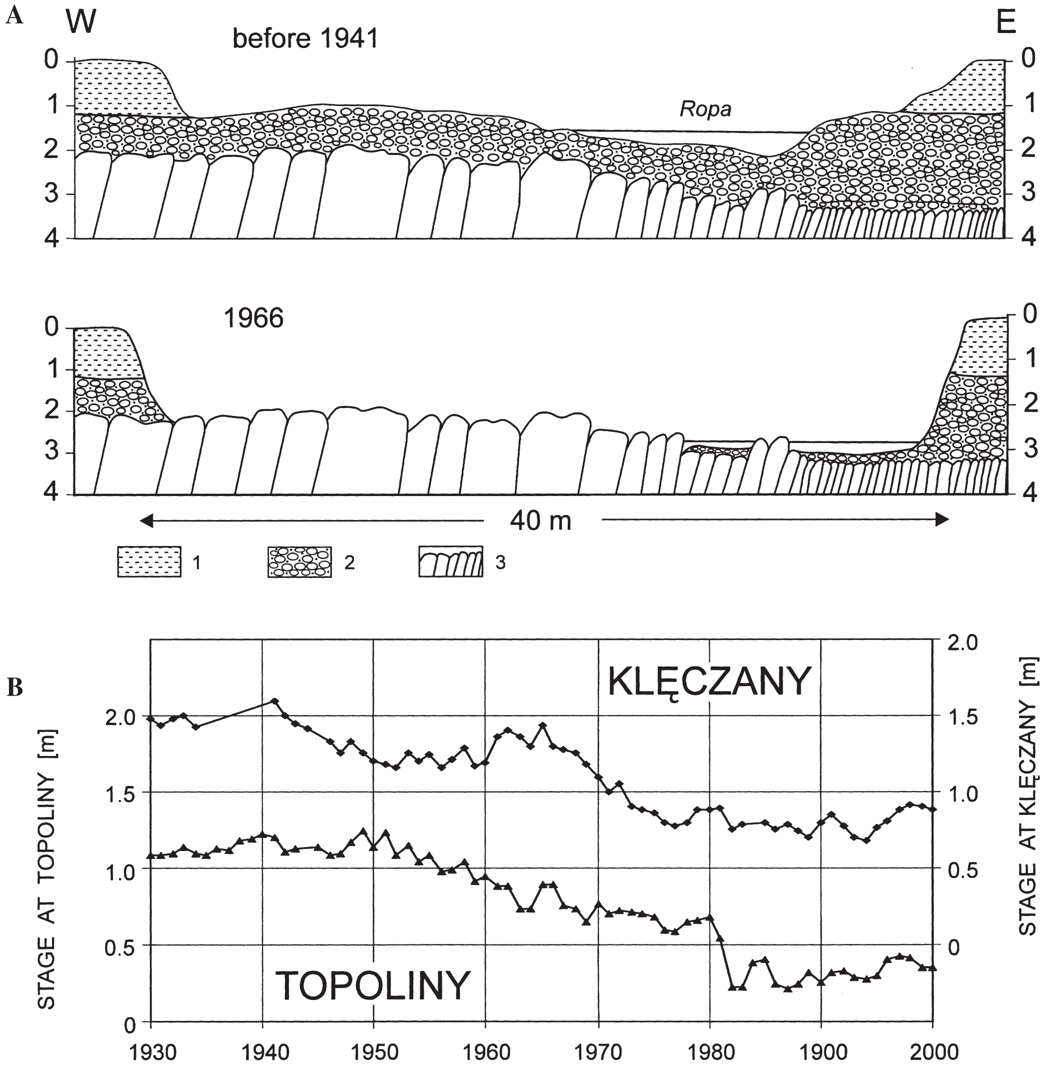

Figure 4. (A) Channel of the Ropa River at Biecz shortly before 1941 and in 1966 (after Augustowski, 1968). 1, fine-grained overbank deposits; 2, gravels; 3, flysch bedrock layers. (B) Changes in the lowest annual water stage of the Ropa River at the Klęczany and Topoliny gauging stations since 1930

(Augustowski, 1968). Second, a considerable increase in mean annual discharge has been found over the last few decades (Lach, 1975; Soja, 1988). This latter impact has been explained by the gauging station now measuring flow that, before channel incision, was conveyed down-valley within the valley floor gravels (Lach and Wyżga, 2002). The increase in streamflow must have involved a considerable loss of the alluvial aquifer storage.

During the 1950s to 1960s sediment was also intensely mined from the channel of the Wisłoka between its confluence with the Ropa and Jasiołka and the river mouth to the Vistula (Figure 3). In this reach, the catchment area increases from 2080 to 4096 km^2 and mean annual discharge changes from 23.7 $\mathrm{m}^3\,\mathrm{s}^{-1}$ at the Krajowice station to 35.0 $\mathrm{m}^3\,\mathrm{s}^{-1}$ at Mielec. Between 1955 and 1964, 2.1 million cubic metres of sediment were mined in the reach (Osuch, 1968). This exploitation was concentrated between 40 and 70 km of the river length (Figure 5 A), where the Wisłoka flows from the Carpathian Foothills onto the foreland basin (Figure 3) and where its bed material consisted of pebble gravel. About 1.5 million m^3 of sediment mined from this section is equivalent to a 0.68 m-thick layer of bed material removed over the pre-mining, bankfull channel width of 77 m (Osuch, 1968).

The volume of sediment taken from the Wisłoka was enormous in comparison with the rate of bed material delivery from upstream, especially since the latter must have considerably decreased in the second half of the 20th century, following the reafforestation of the montane part of the catchment (Lach and Wyżga, 2002) and the gravel mining in the Ropa. Estimation of the sediment transport rate indicated that it would take about 500 years to fully replenish the volume of extracted sediment (Osuch, 1968). Indeed, rapid downcutting of the Wisłoka channel began concurrently with the onset of the intense sediment mining (Figure 5(B)). At the Łabuzie gauging station, minimum annual stage lowered by about 1.3 m between 1953 and the late 1960s, when the in-stream mining was prohibited and exploitation shifted to pits on the valley floor. However, as streambed degradation advanced, the channel was being progressively narrowed by installation of groynes (Wyżga, 1997, 2001b), with the resultant increase in the sediment transport capacity of the river (Wyżga, 2001a). As a consequence, channel incision has continued long after the period of in-stream mining. This was reflected in the lowering of minimum annual stage at Łabuzie by a further 1.2 m between the late 1960s and the mid-1990s, when the vertical position of the channel stabilized (Figure 5(B)). In total, minimum annual stage at the station fell by 2.5 m over the second half of the 20th century, which reflected bed lowering at the gauging section by about 4 m and the simultaneous, considerable reduction in channel width (Figure 5(C)).

Two facts emphasize the importance of the in-stream sediment mining as a cause of incision of the Wisłoka channel. First, although all main rivers of the Polish Carpathians were similarly channelized during the 20th century and, in many of them (excluding the Wisłoka), continuity of sediment transport from the montane parts of their catchments was interrupted by reservoirs, the Wisłoka is characterized by the greatest extent of channel incision over the century (see Figure 1 in Wyżga (2001a)). Second, the greatest extent of incision on the river, over both the whole 20th century and just the second half of that century, was concentrated in the channel section with the most intensive sediment mining (Figures 3 and 5(A)).

The rapid downcutting of the Wisłoka channel has resulted in a number of detrimental effects. Undermining bridge piers and regulation structures, difficulties in the operation of water intakes, and the lowering of groundwater level on the valley floor cause direct economic losses at the local scale (Osuch, 1968; Wyżga, 2001a). More importantly, incision has considerably increased concentration of flood flows in the channel. For instance, the level of bankfull stage of the 1957 channel at Łabuzie, which was then attained at a discharge of 310 $\mathrm{m}^3\,\mathrm{s}^{-1}$ with a 1.8-yr return period (Figure 5(C)), in 1996 could only be reached by a discharge of 610 $\mathrm{m}^3\,\mathrm{s}^{-1}$, having a 6-yr frequency. With the resultant reduction in floodplain retention, a considerable increase in flood hazard has been recorded in the lower course of the river (Wyżga, 1997). Moreover, with the decreased frequency of overbank flows and the increased concentration of water and sediment transfer in the deepened channel, the potential of the river floodplain for sediment storage has been dramatically reduced (Wyżga, 2001b). As a result, the majority of the suspended load of the Wisłoka may now be routed through its incised reach directly to the Vistula, contributing to the rapid channel and floodplain aggradation in the middle course of that river (Łajczak, 1997).

Other cases

In order to have a more general overview and allow for comparison of cases from different contexts, other sufficiently documented cases have been selected from published studies. Results are summarized in Table II, where the cases previously described in detail are also included, to facilitate the comparison with the other cases.

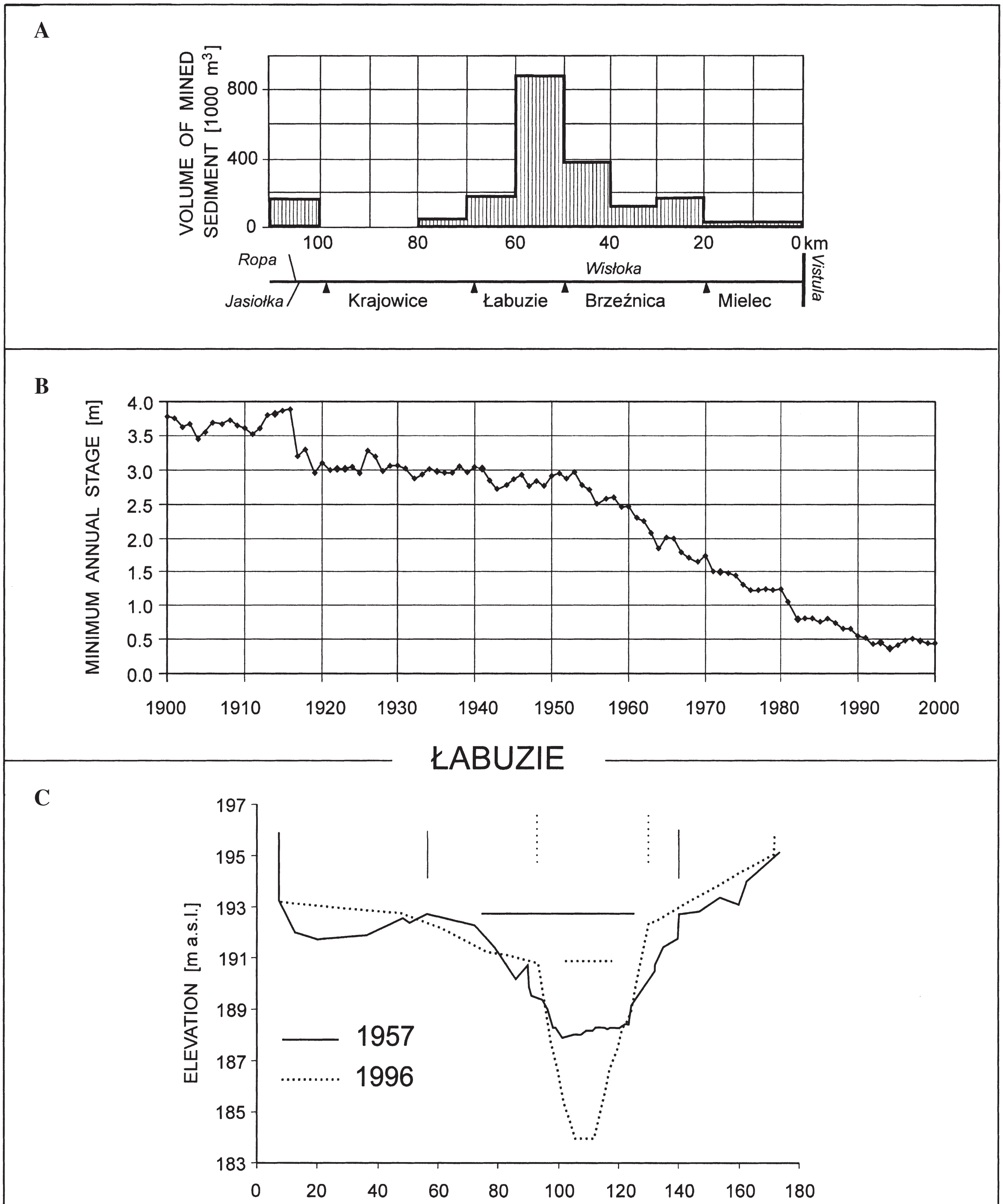

Figure 5. (A) Volume of sediment mined from the Wisłoka channel between 1955 and 1964 shown for 10 km long sections of the river course (modified after, Osuch, 1968). (B) Changes in the lowest annual water stage of the Wisłoka River at the Łabuzie gauging station over the 20th century. (C) Cross-section of the Wisłoka River at the Łabuzie gauging station in 1957 and 1996. Horizontal lines above the cross-section indicate elevation of bankfull stage and vertical lines mark the horizontal extent of the channel in 1957 and 1996

DISCUSSION

From the study cases described in detail and the other cases listed in Table II, it is evident that sediment mining has very significant morphological effects on alluvial rivers. Channel incision is commonly reported as the main morphological effect, with extremely variable amounts of bed degradation, up to maximum values of 12–14 m (Southern California, France, Italy, northeast England). Net aggradation is reported only in one case (White River, Washington) along a fan reach. Lateral instability, width adjustments, and changes in channel pattern are less frequently reported, and are more variable among different rivers. Channel widening associated with incision is reported in one case of a small braided stream (Cache Creek), while in other cases of large braided or wandering rivers (Tagliamento and Brenta) channel narrowing is combined with incision. Channel pattern has sometimes changed from braided to wandering (Piave and Brenta), from braided to single-thread (Stony Creek, Figarella), and in one case from wandering to braided at the extraction sites (Wooler Water).

Time of morphological changes is usually short (typically ranging from 15 to 30 yr), and is strictly associated with the period of sediment mining, with resulting high rates of incision of 0.1–0.2 m yr^{-1}, up to 0.3–0.4 m yr^{-1} in the worst cases. In two cases of ephemeral braided streams of southern California (Tujunga Wash and San Juan Creek), abrupt upstream headcutting, up to 4 and 9 m respectively, during a single, catastrophic flood is reported.

The main control on channel responses and recovery appears to be the ratio between the sediment extraction rate and the replenishment rate, the latter being related to the sediment supply from upstream. Mining conducted at a rate greatly exceeding the rate of material replenishment results in substantial incision and considerable channel adjustments (as in Stony Creek, Wooler Water and the Wisłoka River) whereas the degradation effects are minor or even lacking when extraction and replenishment rates are similar (as in the Satsop and White Rivers).

The initial channel morphology, that in turn is related to the rate of sediment delivery to the river, is also an important factor. Generally, braided rivers receiving high sediment inputs from their catchments will be less vulnerable to mining carried out with a given intensity than sinuous or meandering rivers with lower rates of sediment supply. Large braided rivers with continued widespread extraction but with high replenishment rates have adjusted through moderate incision and narrowing (Tagliamento R.), but ephemeral wash (braided) gravel-bed rivers (California) with extraction rate much larger than replenishment rate (deep, localized pits) have responded with rapid and deep, upstream progressing incision as well as lateral channel instability. Sinuous and meandering rivers, characterized by lower rates of sediment supply from their catchments, have generally reacted with severe incision.

Another factor influencing the types and magnitude of morphological changes and recovery is whether the river is channelized or not. If channel banks are not protected, lateral channel instability allows the river to reduce its transporting power, due to channel widening and increased sinuosity, and to diminish the sediment deficit by eroding the banks, accelerating the recovery processes. In contrast, such adjustment mechanisms are precluded if channel banks are lined with materials resistant to erosion (gabions, rip-rap, concrete walls) or if the thalweg is trained by groynes. This makes streambed degradation the main adjustment mechanism and leads to high amounts of incision.

Finally, the thickness of alluvium underlying rivers subject to mining activity is an important factor determining the amount of incision, the post-mining channel conditions and recovery. Exploitation of sediment from rivers with a thin cover of alluvium may easily lead to the transformation of the former alluvial channels into bedrock ones along long river reaches (as on the Ropa). Although the depth of incision is relatively low in such rivers, the distant location of sediment sources causes very slow recovery. On the other hand, a thick mantle of alluvium on a valley floor enables excavation of very deep pits (as in some rivers of California). While there is no danger of channel transformation into bedrock conditions in such cases, the deep pits generally induce severe incision in longer river reaches.

Other human activities reducing the upstream sediment supply (e.g. land-use changes, including reafforestation, dams) tend to increase the difference between extraction and replenishment rates, accentuating the effects of sediment mining. They also have an important control on the recovery processes after sediment mining has been stopped or decreased. In the case of rivers severely affected by other upstream human activities reducing sediment supply, the morphological changes associated with mining are usually irreversible, while rivers with relatively high sediment supply, untouched by other human disturbances, can recover their original pattern and equilibrium.

Table II. Review of documented cases of effects of sediment mining on alluvial rivers

River and region	Watershed area, channel morphology and bed material	Location and time of sediment mining; volumes or rates of extraction and estimated replenishment rates (when available)	Other disturbances time (during approximately the same period of sediment mining)	Morphological changes: type, location and time	Effects on structures and environment	References
Cache Creek, California, USA	$2978\,km^2$ Braided Gravel-bed	Final reach (14.5 km), since at least 1930s Estimated rates of extraction: $300\,000\,t\,yr^{-1}$ prior 1950, up to $2\,600\,000\,t\,yr^{-1}$ between 1976 and 1986	Construction of diversion dam and irrigation diversions in 1912	Incision by an average of about 4.6 m, up to 8.2 m over a 21-yr period Channel widening	Undermining of all bridges; increased flood capacity; water-table lowering with loss in aquifer storage potential	Collins and Dunne (1990); Kondolf (1997)
Russian River and Dry Creek, California, USA	$3846\,km^2$ Sinuous with alternate bars Gravel-bed	Upper and middle reaches of Russian R. and Dry C. in the lower basin, 1940s–1970s Total volumes extracted (including from terrace): about 23 million tons between 1946 and 1971	Dam at the upper end of the reach (but effects on bedload probably of little significance)	Russian R. (middle reach): incision by an average of 3.5 m, locally up to 6 m, between 1940 and 1972 Dry C.: local degradation between 1964 and 1984 along the extraction sites	Exposure of resistant substrates (clay layers); drop of water levels in some wells; death of riparian vegetation; loss of aquifer storage	Harvey and Schumm (1987); Collins and Dunne (1990); Kondolf (1997)
Tujunga Wash, California, USA	$298\,km^2$ Ephemeral wash (braided) Gravel-bed	Upper alluvial fan; gravel pit along an inactive channel, since 1925		Inactive channel captured during a flood (1969), triggering headward scour (incision greater than 4 m); Incision also downstream due to sediment trapped in the pit	Failure of bridges; lateral instability destroying a long section of highway	Scott (1973), Bull and Scott (1974); Collins and Dunne (1990)

Stony Creek, California, USA		Along the entire alluvial fan reach (concentrated along 5 km), after 1963 Estimated rate of extraction: 260 000–730 000 m^{3} yr^{-1} Estimated replenishment rate (post dam): about 20 000 ^{3} yr^{-1}	Dam (1963)	Incision up to 5 m between 1974 and 1990 Changes in channel morphology from braided to single-thread	Undermining of bridges	Kondolf and Swanson (1993), Kondolf (1994a, 1997)
San Luis Rey River, California, USA	1443 km^{2} Ephemeral wash Sandy gravel-bed	Medium reach (several deep pits), since late 1980s Permitted extraction rate of 5 pits: 300 000 m^{3} yr^{-1}, corresponding to about 50 times the estimated (post-dam) replinishment rate	Dam (1923) in the upper portion of the basin	Upstream headcutting (including tributaries) and downstream incision. Average degradation of 3.1 m between 1973 and 1993	Exposure of bridge piers, aqueducts, and gas pipelines; failure of bridge along tributary	Kondolf and Larson (1995); Sandecki and Avila (1997)
San Juan Creek, Southern California	144 km^{2} Ephemeral wash (braided) Gravel-bed	Instream gravel pit (since 1977) with average depth of 13.7 m Estimated volume extracted: 1 700 000 m^{3}		Channel instability following a flood (1978): upstream headcutting (up to 9 m) (including tributaries) and widening; refill of the pit and downstream incision		Simons *et al*. (1979); Galay (1983); Chang (1988)
Humptulips River, Washington, USA	Gravel-bed	Medium-lower course, 1950s–1980s Estimated rates: between 25 000 m^{3} yr^{-1} and 55 000 m^{3} yr^{-1} Estimated replenishment rates: 1500–5000 m^{3} yr^{-1}		Medium course: incision (1960–1980) of about 0.6 m.		Collins and Dunne (1989, 1990)

Continues

Table II. Continued

River and region	Watershed area, channel morphology and bed material	Location and time of sediment mining; volumes or rates of extraction and estimated replenishment rates (when available)	Other disturbances time (during approximately the same period of sediment mining)	Morphological changes: type, location and time	Effects on structures and environment	References
Wynoochee River, Washington, USA	Gravel-bed	Medium-lower course Documented mining activity between 1960 and 1980s Estimated rates: between 8000 $m^3 yr^{-1}$ (beginning 1960s) and 75 000 $m^3 yr^{-1}$ (1982) Estimated replenishment rates: 3000–7000 $m^3 yr^{-1}$	Dam (1972)	Upstream reach: slow degradation from mid-1930s to early 1960s (total of about 0.2 m) followed by equal aggradation (1960s–1980s) Downstream: stable (1956–1966), then incision (1966–1986) of about 0.5 m.		Collins and Dunne (1989, 1990)
Satsop River, Washington, USA	Sinuous-meandering Gravel-bed	Lower course, 1940s–1980s Estimated rates: average of 15 000 $m^3 yr^{-1}$ (beginning in the mid-1960s), up to 30 000 $m^3 yr^{-1}$ (1982) Estimated replenishment rates: about 8 000 $m^3 yr^{-1}$		Aggradation (1943–1951) of about 0.5 m, then incision (1952–1986) of about 0.8 m.		Collins and Dunne (1989, 1990)
White River, Washington, USA	Gravel-bed	Along a fan reach, at the junction of a canyon reach and the lowland, since beginning of 1900 Estimated rates: minimum of 53 500 $m^3 yr^{-1}$ between 1975 and 1985 Estimated replenishment rate: about 92 500 $m^3 yr^{-1}$	Diversion (1906) from Duwamish R. to Puyallup R.	Aggradation (1945–1961) of about 1.4 m, then stable between 1962 and 1971		Collins and Dunne (1990)

Po River, north Italy	70 091 km^2 Meandering	All alluvial plain reaches, particularly intense from 1950s to 1980s	Interventions at basin level (construction of weirs, reafforestation), particularly during the period 1880–1930	Incision (1–6 m) along all alluvial reaches; two phases of incision: minor phase from the end of 1800 to 1960; second phase from 1960 to 1990s	Undermining of bridges and bank protections; loss of groundwater resources	Govi and Turitto (1993); Lamberti and Schippa (1994)
Piave River, northeast Italy	3899 km^2 Braided Gravel-bed	Mountain and alluvial plain reaches; 1960s–1980s	Dams, diversions (from 1930s)	Incision (up to 2–3 m); channel narrowing (width reduction of 63% in the last century), decrease of braiding index, change in channel morphology (from braided to wandering)	Loss of groundwater resources	Surian (1999, 2005)
Brenta River, northeast Italy	1567 km^2 Braided and single-thread Gravel-bed	Alluvial plain reaches; intense between 1950s to 1980s	Dam (1954)	Incision (up to 7–8 m) Channel narrowing (width reduction of 58% in the last two centuries), with change in morphology from braided to wandering and from braided to single-thread	Failure of bridges, loss of groundwater resources; increased flood hazard to downstream reaches	Castiglioni and Pellegrini (1981); Surian (2005)
Tagliamento River, northeast Italy	2580 km^2 Braided Gravel-bed	Alluvial plain reaches; intense between 1970s to 1980s; more than 24 million m^3 from 1970 to 1991		Incision (up to 3 m); narrowing (width reduction of 53% in the last two centuries); decrease of braiding index	Loss of groundwater resources	Surian (2005)
Arno River, central Italy	8830 km^2 Single thread (sinuous to meandering) Predominantly gravel-bed (sandy gravel in the lower and coastal plain reach)	All alluvial and coastal plain reaches, since the beginning of 20th century, particularly intense from 1950s to 1980s	Interventions at basin level (construction of weirs, reafforestation), particularly during the period 1880–1930 Dams (1957)	Incision (2–5 m on average, up to 9 m) along all alluvial and coastal plain reaches; two phases of incision: minor phase from the beginning of 20th century; second phase from 1945–60 to 1990s	Damage to bridges, bank protections and levees; upstream migration on tributaries; riverbanks instability; loss of groundwater resources; beach erosion	Billi and Rinaldi (1997); Rinaldi and Simon (1998); Agnelli *et al.* (1998)

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Table II. Continued

River and region	Watershed area, channel morphology and bed material	Location and time of sediment mining; volumes or rates of extraction and estimated replenishment rates (when available)	Other disturbances time (during approximately the same period of sediment mining)	Morphological changes: type, location and time	Effects on structures and environment	References
Jarama River, central Spain	Sinuous Medium to coarse gravels and sands	Since 1960s up to the nowadays; in 1999 more than 30% of the floodplain was occupied by mining activities	Dams, embankments and dredging	Incision up to 4 m; channel narrowing; reduction of area occupied by bars	Damage to bridges and dikes	Uribelarrea *et al.* (2003)
Fluvià River, Spain	1125 km^2 Meandering	Coastal plain; since 1980s		Incision up to 2.5 m	Effects on groundwater quantity and quality (loss of stored water volume and salt water intrusion)	Mas-Pla *et al.* (1999)
Arve River, southeast France	Braided Gravel-bed	Since 1950s; volume extracted: more than 100 000 m^3 yr^{-1}		Incision (between 3 and 10 m); channel narrowing; decrease of channel slope; change in channel morphology (from braided to single-thread)		Peiry (1987)
Drôme River, southeast France	1640 km^2 Braided Gravel-bed	1970s–1980s		Incision: often exceeds 2 m, locally 4–5 m	Damage to bridges and dikes; water resources	Piégay *et al.* (1997)
Figarella and Fium Seccu, western Corsica, France	Figarella: 137 km^2 F. Seccu: 63 km^2 From mountain streams to piedmont braided-wandering Coarse gravel-bed	Figarella: two pits along the last 3 km, from 1972 to 1992 F. Seccu: pit at the outlet from 1996 to 1970, about 20 000 m^3		Figarella: upstream and downstream incision and bed coarsening, abandonment of secondary channels, change from braided to single-thread F. Seccu: less remarkable changes upstream	Beach erosion	Gaillot and Piégay (1999)

Rhône River, south-east France	20 300 km^2 to Lyon Sinuous Gravel-bed	By-passed reach (Miribel canal) in the middle course Industrial gravel mining since 1957, 1.5 million tons extracted between 1974 and 1991	Construction of diversion dam in 1899; Slopes and floodplain reafforestation in the headwaters, dams on tributaries	Up to 4 m of bed degradation between 1952 and 1990 resulting in considerable channel deepening Entrenchment of low-flow channel	Undermining of bank protections; water table lowering	Petit *et al.* (1996)
Wooler Water, north-east England	52.5 km^2 Wandering Gravel-bed	Four extraction areas along a reach 2.5 km in length, 1925–1970 Extraction yield: about 32 000 m^3 yr^{-1}, corresponding to about 222 times the estimated replenishment rate		Incision (up to about 9 m between 1966 and 1995) Channel planform instability (spatial and temporal alternated changes in channel width, braiding index and sinuosity) Changes in channel morphology: from wandering to braided for the extraction sites, and to straight/sinuous downstream	Exposure of foot-bridge piers	Sear and Archer (1998)
Ropa River, southern Poland	970 km^2 of low mountain to foothill area Sinuous Gravel-bed	Short foothill reach, 1940s–1960s; Volumes extracted >1 million m^3	Catchment reafforestation after mid-1940s	Incision down to bedrock (1.5 m at the mining site, in 1940s–1960s) progressing up- and downstream in 1940s–1980s	Loss of floodplain retention; loss of groundwater resources and increase in streamsflow	Augustowski (1968) Lach (1975)
Wisłoka River, southern Poland	4096 km^2 of low mountain to foreland area Sinuous Sandy gravel-bed	Foothill and foreland reaches, 1950s–1960s; volumes extracted: about 2.1 million m^3, estimated time of replenishment: about 500 yr	Reafforestation of montane part of catchment after mid-1940s; Channelization in 1950s–1970s	Up to 2.6 m of incision and channel narrowing in foothill and foreland reaches during 1950s–1990s	Damage to bridges and bank protections; problems with operation of water intakes; reduced crop yields due to fall of ground-water level; increased flood hazard to down-stream reaches; reduced sediment storage on floodplain	Osuch (1968); Wyżga (1997, 2001b)

Continues

Table II. Continued

River and region	Watershed area, channel morphology and bed material	Location and time of sediment mining; volumes or rates of extraction and estimated replenishment rates (when available)	Other disturbances time (during approximately the same period of sediment mining)	Morphological changes: type, location and time	Effects on structures and environment	References
Lower Manawatu River, New Zealand	5957 km^2 First reach: low-sinuosity channel, coarse-grained gravel Second reach: highly sinuous, fine sand and silt	Various locations since 1900s Documented rates (1965-1985, reach of 37 km in length) of about 190 000 m^3 yr^{-1} (about 2–3 times the estimated replenishment rate)		Incision: about 0.25 m between 1967 and 1976 by repeated cross-sections; about 1.1 m from 1964 to 1977 and about 0.5 m from 1972 to 1977 at two gauging stations		Page and Heerdegen (1985); Collins and Dunne (1990)
Tweed River, New South Wales, Australia	Estuary of sand-bed river	Entrance region of the river estuary; 1.5 million m^3 of sand extracted between 1966 and 1976		Occurrence of a dredge hole inducing movement of sand bedforms from both upstream and estuary entrance	Increased tidal penetration into the estuary; increased tidal range; greater peak tidal discharge	Erskine (1990)
Nepean River, New South Wales, Australia	21740 km^2 Meandering with alternating alluvial and bedrock reaches Sand-bed	Weir pools located in upper alluvial reaches Extraction rate: about 135 000 t yr^{-1} between 1968 and 1990 Estimated replenishment rate: 60 000 t yr^{-1}	Main river and its tributaries impounded by a series of dams and weirs	Depth of dredged weir pools increased by 140% and width increased by 73%, with storage capacity of the pools increased by 180–250% between 1978 and 1987; Upstream progressing degradation leading to formation of deep scour hole at the base of the upstream weir Straightening and widening of the channel in unextracted sections	Failure of weirs; destabilization of banks; oxygen and thermal stratification in weir pools; removal of coarse woody debris; reduced abundance of native fish; loss of submerged macrophytes and riparian plants	Erskine (1997); Erskine and Green (2000)

MANAGEMENT OF SEDIMENT MINING: PROBLEMS AND PERSPECTIVES

On the basis of the data discussed in this study and on common practices carried out by agencies involved with river management, it can be concluded that management of sediment mining has often been very crude and poorly based upon scientific knowledge. Despite many adverse morphological, ecological and environmental effects of sediment mining from alluvial channels, such effects are seldom taken into account in the decisions concerning sediment exploitation. This may be for the following reasons (Collins and Dunne, 1989, 1990; Kondolf, 1994a, 1994b, 1997; Erskine and Green, 2000): (i) poor knowledge of the effects among river managers, reflecting insufficient documentation of such effects in the hitherto published literature; (ii) ignoring the environmental costs of exploitation in cost-benefit analysis, which makes active channels much more profitable source of sediment compared to other alternatives, and (iii) considering the evaluation of potential effects of exploitation as an unnecessarily expensive and time-consuming procedure.

Even in countries where sediment mining has been formally prohibited (e.g. Italy, Poland), in many cases permissions are still granted under the motivation of increasing channel capacities for floodwater and preventing erosion of undercut concave banks positioned against channel bars. River managers justify these permissions arguing that they allow extraction of only such amounts of sediment that are compensated for by the transport from upstream. While such practices are extremely harmful in the case of incised rivers, which are common in Western, Central and Southern Europe, they are also improper for hitherto vertically stable rivers. Although removal of the amounts of bed material comparable to those which are delivered from upstream may have no negative effects on the upstream reach, it starves the river below the place of exploitation, thus inducing incision in that reach. Therefore, given the number of detrimental effects of sediment mining from active channels, it is imperative to eliminate the practice from incised, incising and vertically stable rivers. However, it should be recognized that if a river is aggrading, exploitation of bed material from its channel may in some cases have beneficial effects for flood-control purposes, channel stability and restoration.

For these reasons, a different approach to sediment mining is needed, in which two issues are crucial: (i) knowledge and management of sediments at basin scale; (ii) a wider application of the available scientific knowledge, particularly of fluvial geomorphology and hydraulics. In particular, granting permissions for extraction and management of mining activity should require an accurate analysis of the following aspects:

(1) A general analysis of the fluvial system (basin- and reach-scale analysis) aimed to identify whether conditions for sediment mining exist. The analysis implies examination of the following aspects: (a) past and present trends of channel adjustments; (b) sources of sediments in the basin and along the river; (c) modes and times of sediment transfer through the fluvial system; (d) presence of natural (e.g. lakes) or artificial features (e.g. dams, weirs) altering sediment fluxes through the system. At the end of this phase, two essential conditions are required if sediment mining is to be considered: (i) the river is aggrading; and (ii) sediment production in the drainage basin is high and sediments are frequently delivered to the river.

(2) Provided these conditions are met, the analysis should then address:
   - —identification of possible sites for sediment extraction. Aggrading reaches along the river must be determined based on past and present trends of channel adjustments.
   - —determination of extraction rates. An evaluation of sediment supply from upstream, by available measurement data or using sediment transport equations, should be required. The rate of extraction must be considerably lower than the rate at which bed material is supplied from upstream (replenishment rate) and, in an ideal case, it should correspond to the excess of sediment influx over transport capacity of the reach, which leads to bed aggradation. This excess (and possible sediment extraction volumes) should be evaluated by constructing a sediment budget for the reach and calculating possible bed level changes by the sediment continuity equation.
   - —prediction of induced effects. Morphological, hydraulic, ecological and environmental effects of sediment mining should be evaluated. For instance, if some amount of bed-level lowering is predicted, a check on its effects on bank stability should be required. When possible, the use of morphological numerical models to define scenarios of future channel adjustments (their type and amounts) is highly desirable.

(3) Monitoring programme. In order to assess the effectiveness of mining and its effects, a monitoring programme is required. It should comprise monitoring of: the volume of extracted sediment; channel changes (a series of

cross-sections has to be established and periodic topographic surveys have to be carried out); and hydraulic and ecological conditions of the river.

(4) Management. Based on the monitoring results, permitted extraction quantities should be periodically reviewed and, if necessary, exploitation should be stopped.

Summarizing, this alternative approach to sediment-mining management and specifically examination of several aspects of the fluvial system mentioned above should help prevent harmful mining practices along rivers. In incised, incising and vertically stable rivers, sediment mining must not be allowed, and exploitation should be moved to valley-floor pits or other sources of sediment (e.g. reservoir deltas) must be found. In aggrading rivers, sediment mining can be considered at locations where it may have beneficial effects for flood-control purposes, channel stability and restoration, though an accurate geomorphic study is mandatory.

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REFERENCES

Agnelli A, Billi P, Canuti P, Rinaldi M. 1998. *Dinamica Evolutiva Recente dell'alveo del Fiume Arno*. Monografia CNR-GNDCI, Publication no. 1739, Pacini Editore: Pisa.

Augustowski B. 1968. Spostrzeżenia nad zmianami antropogenicznymi w korycie rzeki Ropy w Karpatach w okolicy Biecza (Observations on man-caused changes in the channel of the River Ropa in the Carpathians), in Polish, with English summary. *Zeszyty Geograficzne Wyższej Szkoly Pedagogicznej w Gdańsku* **10**: 161–168.

Autorità di Bacino dei fiumi dell'Alto Adriatico 1998. piano di bacino del Fiume Tagliamento: piano stralcio per la sicurezza idraulica del medio e basso corso. Venice.

Billi P, Rinaldi M. 1997. Human impact on sediment yield and channel dynamics in the Arno River basin (central Italy). In *Human Impact on Erosion and Sedimentation*, Walling DE, Probst JL (eds). Publication no. 245, International Association of Hydrological Scientists: Wallingford; 301–311.

Bravard JP, Amoros C, Pautou G, Bornette G, Bournaud M, Creuzé des Châtelliers M, Gibert J, Peiry JL, Perrin JF, Tachet H. 1997. River incision in South-east France: morphological phenomena and ecological effects. *Regulated Rivers: Research and Management* **13**: 1–16.

Brookes A. 1988. *Channelized Rivers: Perspectives for Environmental Management*. John Wiley and Sons: Chichester.

Brown AV, Lyttle MM, Brown KB. 1998. Impacts of gravel mining on gravel bed streams. *Transactions of the American Fisheries Society* **127**(6): 979–994.

Bull WB, Scott KM. 1974. Impact of mining gravel from urban stream beds in the southwestern United States. *Geology* **2**: 171–174.

Castiglioni GB, Pellegrini GB. 1981. Geomorfologia dell'alveo del Brenta nella pianura tra Bassano e Padova. In *Il Territorio della Brenta*, Zunica M (ed.). Amm. Prov. di Padova—Università di Padova; 12–32.

Chang HH. 1988. *Fluvial Processes in River Engineering*. Krieger Publishing: Malabar, FL, USA.

Church M, Ham D, Weatherly H. 2001. Gravel management in lower Fraser River. Report prepared for the City of Chilliwack, British Columbia.

Collins BD, Dunne T. 1989. Gravel transport, gravel harvesting, and channel-bed degradation in rivers draining the southern Olympic Mountains, Washington, USA. *Environmental Geology and Water Science* **13**(3): 213–224.

Collins B, Dunne T. 1990. Fluvial geomorphology and river-gravel mining: a guide for planners, case studies included. Special Publication 98, California Department of Conservation, Division of Mines and Geology.

Cote IM, Vinyoles D, Reynolds JD, Doadrio I, Perdices A. 1999. Potential impacts of gravel extraction on Spanish populations of river blennies *Salaria fluviatilis* (Pisces, Blenniidae). *Biological Conservation* **87**(3): 359–367.

Dunne T, Leopold LB. 1978. *Water in Environmental Planning*. W.H. Freeman: San Francisco.

Erskine WD. 1990. Environmental impacts of sand and gravel extraction on river systems. In *The Brisbane River: A Source Book for the Future*, Davie P, Stock E, Low Choy D (eds). Australian Littoral Society: Brisbane; 295–302.

Erskine WD. 1997. The real environmental costs of sand and soil mining on the Nepean River, NSW. In *Science and Technology in the Environmental Management of the Hawkesbury-Nepean Catchment*, Riley SJ, Erskine WD, Shreshta S (eds). Geographical Society of New South Wales Conference Papers 14: 29–35.

Erskine WD, Green D. 2000. Geomorphic effects of extractive industries and their implications for river management: the case of the Hawkesbury-Nepean River, New South Wales. In *River Management: The Australasian Experience*, Brizga S, Finlayson B (eds). John Wiley and Sons: Chichester; 123–149.

Forshage A, Carter NE. 1973. Effects of gravel dredging on the Brazos River. *Proceedings of the 27th Annual Conference, Southeastern Association Game and Fish Commission* vol. 24, 695–708.

Gaillot S, Piégay H. 1999. Impact of gravel mining on stream channel and coastal sediment supply: example of the Calvi Bay in Corsica (France). *Journal of Coastal Research* **15**(3): 774–788.

Galay VJ. 1983. Causes of river bed degradation. *Water Resources Research* **19**(5): 1057–1090.

Girel J, Doche B. 1983. Influence des activités humaines sur la génèse, l'évolution et la disparition de groupements végétaux alluviaux. *Revue de Géographie Alpine* **71**(4): 343–351.

Govi M, Turitto O. 1993. Processi di dinamica fluviale lungo l'asta del Po. *Acqua-Aria* **6**: 575–588.

Harvey MD, Schumm SA. 1987. Response of Dry Creek, California, to land use change, gravel mining and dam closure. In *Erosion and Sedimentation in the Pacific Rim*, Beschta RL, Blinn T, Grant GE, Ice GG, Swanson FJ (eds). Publication no. 165, International Association of Hydrological Scientists: Wallingford; 451–460.

Hatva T. 1994. Effect of gravel extraction on groundwater. In Future Groundwater Resources at Risk, Soveri J, Suokko T (eds). Publication no. 222, International Association of Hydrological Scientists Wallingford; 427–434.

Kira H. 1972. Factors influencing the river behaviour: river bed variation due to dam construction and gravel gathering. In *Transactions of the 8th Congress of the International Commission on Irrigation and Drainage*, Varna, Bulgaria, 5: 29.1; 405–432.

Kondolf GM. 1994a. Geomorphic and environmental effects of instream gravel mining. *Landscape and Urban Planning* **28**: 225–243.

Kondolf GM. 1994b. Environmental planning in regulation and management of instream gravel mining in California. *Landscape and Urban Planning* **29**: 185–199.

Kondolf GM. 1997. Hungry water: effects of dams and gravel mining on river channels. *Environmental Management* **21**(4): 533–551.

Kondolf GM, Larson M. 1995. Historical channel analysis and its application to riparian and aquatic habitat restoration. *Aquatic Conservation* **5**: 109–126.

Kondolf GM, Swanson ML. 1993. Channel adjustments to reservoir construction and instream gravel mining, Stony Creek, California. *Environmental Geology and Water Science* **21**: 256–269.

Lach J. 1975. Ewolucja i typologia krajobrazu Beskidu Niskiego z uwzględnieniem gospodarczej działalności człowieka (Evolution and typology of the landscape in the Low Beskid Mts with special consideration of the economic activity of man), in Polish, with English summary. *Prace Monograficzne Wyższej Szkoły Pedagogicznej w Krakowie* **16**: 5–72.

Lach J, Wyżga B. 2002. Channel incision and flow increase of the upper Wisłoka River, southern Poland, subsequent to the reafforestation of its catchment. *Earth Surface Processes and Landforms* **27**: 445–462.

Lagasse PF, Winkley BR, Simons DB. 1980. Impact of gravel mining on river system stability. *Journal of Waterway, Port, Coastal and Ocean Division, ASCE* **106**: 389–404.

Łajczak A. 1997. Anthropogenic changes in the suspended load transportation by and sedimentation rates of the River Vistula, Poland. *Geographia Polonica* **68**: 7–30.

Lamberti A, Schippa L, 1994. Studio dell'abbassamento dell'alveo del Fiume Po: previsioni trentennali di abbassamento a Cremona. *Navigazione Interna*, no. 3–4 (Suppl.).

Lane EW. 1947. Grade changes in Cherry Creek, Denver. *Eos, Transactions of the American Geophysical Union* **28**(3): 443–444.

Lee HY, Fu DT, Song MS. 1993. Migration of rectangular mining pit composed of uniform sediments. *Journal of Hydraulic Engineering* **119**(1): 64–80.

Maraga F, Mortara G. 1981. Le cave per inerti lungo i corsi d'acqua: rapporti con la dinamica fluviale. *Bollettino Associazione Mineraria Subalpina* **18**(3–4): 385–395.

Marston RA, Bravard J-P, Green T. 2003. Impacts of reforestation and gravel mining on the Malnant River, Haute-Savoie, French Alps. *Geomorphology* **55**: 65–74.

Mas-Pla J, Montaner J, Solà J. 1999. Groundwater resources and quality variations caused by gravel mining in coastal streams. *Journal of Hydrology* **216**: 197–213.

Mossa J, McLean M. 1997. Channel planform and land cover changes on a mined river floodplain. Amite River, Louisiana, USA. *Applied Geography* **17**: 43–54.

Osuch B. 1968. Problemy wynikąjace z nadmiernej eksploatacji kruszywa rzecznego na przykładzie rzeki Wisłoki. *Zeszyty Naukowe Akademii Górniczo-Hutniczej* **219**: 283–301.

Page KJ, Heerdegen RG. 1985. Channel change in the lower Manawatu river. *New Zealand Geographer* **41**: 34–38.

Peiry JL. 1987. Channel degradation in the middle Arve river, France. *Regulated Rivers: Research and Management* **1**: 183–188.

Petit F, Poinsart D, Bravard J-P. 1996. Channel incision, gravel mining and bedload transport in the Rhône river upstream of Lyon, France ('canal de Miribel'). *Catena* **26**: 209–226.

Piégay H, Landon N, Bravard JP, Clément P, Liebault F. 1997. Channel incision and potentiality of reversability. The Drôme River case, France. In *Management of Landscapes Disturbed by Channel Incision*, Wang SSY, Langendoen EJ, Shields FD (eds). Center for the Computational Hydroscience and Engineering, University of Mississippi: Oxford, MS; 488–493.

Prudhomme P. 1975. Aménagement du Var inférieur et protection des nappes souterraines: un example d'extraction contrôlée de graviers (Development of the lower course of the River Aar and protection of its aquifer. An example of controlled gravel extraction), in French, with English summary. *La Houille Blanche* **2–3**: 145–153.

Radecki-Pawlik A. 2002. Pobór żwiru i otoczaków z dna potoków górskich (Mining of gravel and cobbles from mountain stream beds), in Polish, with English summary. *Aura* **2**: 17–19.

Rinaldi M. 2003. Recent channel adjustments in alluvial rivers of Tuscany, Central Italy. *Earth Surface Processes and Landforms* **28**(6): 587–608.

Rinaldi M, Simon A. 1998. Bed-level adjustments in the Arno River, Central Italy. *Geomorphology* **22**(1): 57–71.

Sandecki M, Avila CC. 1997. Channel adjustments from instream mining: San Luis Rey River, San Diego County, California. In *Storm-Induced Geologic Hazards: Case Histories from the 1992–1993 Winter in Southern California and Arizona*, Larson RA, Slosson JE (eds). Reviews in Engineering Geology no. 11, Geological Society of America: Boulder, CO, USA; 39–48.

Sato N. 1971. Changes in river bed in three main rivers in Nishi-Ou District, north-east Honshu. *Geographical Review of Japan* **44**: 356–365.

Sato N. 1975. On the changes of river bed in the Oyodo River and its influence on the drainage basin. *Japanese Journal of Limnology* **36**: 33–47.

Scott KM. 1973. Scour and fill in Tujunga Wash—a fan-head valley in urban southern California. *U.S. Geological Survey Professional Paper 732-B*.

Sear DA, Archer D. 1998. Effects of gravel extraction on stability of gravel-bed rivers: the Wooler Water, Northumberland, UK. In. *Gravel-Bed Rivers in the Environment*, Klingeman PC, Beschta RL, Komar PD, Bradley JB (eds). Water Resources Publications, LLC: Highlands Ranch, CO, USA; 415–432.

Simons DB, Lagasse PF. 1976. Impact of dredging on river system morphology. In *Proceedings of Conference Rivers '76.* American Society of Civil Engineers: New York; 435–457.

Simons DB, Li RM, Duong N. 1979. Overview of case studied and data management. In *Analysis of Watersheds and River Systems*, 16–8, Colorado State University, Fort Collins, CO.

Soja R. 1988. Zmiana odpływu w zlewni Wisłoki pod wpływem działalności człowieka (Change of the Wisłoka River run-off under the impact of the human activity), in Polish, with English summary. *Dokumentacja Geograficzna* **4**: 9–22.

Surian N. 1999. Channel changes due to river regulation: the case of the Piave River, Italy. *Earth Surface Processes and Landforms* **24**: 1135–1151.

Surian N. 2005. Effects of human impact on braided river morphology: examples from Northern Italy. In *Braided Rivers*, Sambrook Smith GH, Best JL, Bristow C, Petts GE (eds). IAS Special Publication: Blackwell Science (in press).

Surian N, Rinaldi M. 2003. Morphological response to river engineering and management in alluvial channels in Italy. *Geomorphology* **50**: 307–326.

Tagliavini S. 1978. Le modificazioni geomorfologiche ed idrogeologiche conseguenti all'attività estrattiva nella conoide del torrente Enza. In *Proceedings of the Conference*. '*Attività estrattiva dei materiali inerti da costruzione: effetti sugli ambienti e risorse alternative*', Cavriago, Italy, 17 March 1978.

Uribelarrea D, Pérez-Gonzalez A, Benito G. 2003. Channel changes in the Jarama and Tagus rivers (central Spain) over the past 500 years. *Quaternary Science Reviews* **22**: 2209–2221.

Ward JV, Tockner K, Edwards PJ, Kollmann J, Bretschko G, Gurnell AM, Petts GE, Rossaro B. 1999. A reference river system for the Alps: the 'Fiume Tagliamento'. *Regulated Rivers: Research and Management* **15**: 63–75.

Wyżga B. 1993. River response to channel regulation: case study of the Raba River, Carpathians, Poland. *Earth Surface Processes and Landforms* **18**: 541–556.

Wyżga B. 1997. Methods for studying the response of flood flows to channel change. *Journal of Hydrology* **198**: 271–288.

Wyżga B. 2001a. A geomorphologist's criticism of the engineering approach to channelization of gravel-bed rivers: case study of the Raba River, Polish Carpathians. *Environmental Management* **28**: 341–358.

Wyżga B. 2001b. Impact of the channelization-induced incision of the Skawa and Wisłoka Rivers, southern Poland, on the conditions of overbank deposition. *Regulated Rivers: Research and Management* **17**: 85–100.