ISSN: 0214-1744

SEDIMENT DEFICIT IN RIVERS CAUSED BYDAMS AND INSTREAM GRAVEL MINING. A REVIEW WITH EXAMPLES FROM NE SPAIN

Déficit de sedimento fluvial a causa de las presas y las extracciones de áridos. Revisión con ejemplos del NE de España

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Abstract: Rivers carry sediment almost continuously from headwaters to deposition zones. Dams and gravel mining interrupt such continuity, causing severe damages to downstream fluvial and coastline ecosystems. Sediment deficit is not only an environmental issue, but also a socio-economic problem. Sediment captured by reservoirs reduces their capacity to store water, and infrastructures in rivers and beaches are also strongly affected by lack of sediment. Sediment deficit and its effects are illustrated in this report with examples from NE Spain, focusing on the Ebro River and rivers in the Catalan Coastal Ranges and Eastern Pyrenees. Over the long-term, sound programmes must be definitively implemented to monitor sediment transfer in river systems and changes over time. But, in the meantime, short-term correction steps should be undertaken, including a) for gravel mining, prohibition in strongly unbalanced rivers, especially in reaches downstream of dams, adding of environmental costs into the price of product (aggregate), and exploring alternative sources of aggregate (concrete recycling, reservoir deposits), and b) for regulated rivers, sediment-pass through in reservoirs only during high flows, and mechanical removal from reservoirs together with flushing flows for artificial sediment nourishment downstream, to prevent (or restore) lost of fish habitat and delta regression.

Keywords: sediment transport, rivers, dams, gravel mining

Resumen: Los ríos transportan el sedimento casi de manera continua desde las cabeceras de las cuencas hasta las áreas de sedimentación aguas abajo. Las presas y las extracciones de áridos interrumpen esa continuidad, causando importantes alteraciones en los ecosistemas fluviales y costeros. El déficit de sedimento no es sólo un problema ambiental sino también socioeconómico. El sedimento retenido en los embalses reduce su capacidad y vida útil, mientras que las infraestructuras en ríos y playas pueden padecer desperfectos debido a la falta de suministro sedimentario. Esta revisión ilustra las causas y los efectos del déficit de sedimento con ejemplos del NE de España, incluidas la cuenca del Ebro y las cuencas de las Cordilleras Costeras Catalanas y el Pirineo Oriental. A largo plazo deben ponerse en funcionamiento programas de control del transporte de sedimento en sistemas fluviales. No obstante, a corto plazo deberían tomarse medidas para corregir estos desequilibrios, entre ellas: a) por lo que se refiere a las extracciones de áridos, prohibición estricta en ríos con fuerte déficit de sedimento, especialmente en sectores aguas abajo de embalses, inclusión de los costos ambientales en el precio del producto (áridos), y búsqueda de nuevas fuentes de sedimento (reciclaje de derribos, extracción en deltas de embalses) y, b) con relación a las presas, liberación de sedimento durante crecidas de cierta magnitud, y extracción mecánica de los embalses como a fuente alternativa para la alimentación artificial durante crecidas artificiales, como técnica para prevenir (o restaurar) la pérdida de hábitat ictícola y la regresión de playas.

Palabras clave: transporte de sedimento, ríos, presas, extracción de áridos

S.E.G.

R. J. Batalla (2003) Sediment deficit in rivers caused by dams and instream gravel mining. A review with examples from NE Spain. *Rev. C. & G.*, 17 (3-4), 79-91.

1. State of the art of sediment deficit in regulated and mined rivers

1.1. Continuity of sediment transport in river systems

Viewed over the long term, runoff erodes the land surface, and the river network carries the erosional products from drainage basins. The idealized watershed can be divided into three zones: that of erosion or sediment production (steep, rapidly eroding headwaters), transport (through which sediment is moved more or less without net gain or loss), and deposition (Schumm, 1977). The river channel in the transport reach can be seen as a conveyor belt (Kondolf, 1994), which transports the erosional products downstream to the ultimate depositional sites below sea level. Changes in river sediment grain size occur downstream, reflecting sorting by water circulating and the effects of weathering and abrasion. Transport of sediment through the catchment and along the river system is continuous. Increased erosion in catchment headwaters as well as reduction in sediment loads propagate downstream through the river network for years and decades (Kondolf, 1997).

Ariver channel is a dynamic feature that constitutes, together with its floodplain, a single hydrological and geomorphic unit characterized by frequent transfers of water and sediment between them and downstream. The failure to appreciate the integral connection of all river reaches, through its water and sediment, and from the headwaters to the deposition zones (a delta, for example), underlies many environmental problems in river management today (Kondolf, 1997).

1.2. Effects of dams

Reservoirs trap all bedload sediment (the coarser part of the sediment load, that moves in intermittent contact with the bed by rolling, sliding, and saltating), and an important part of the suspended sediment load (finer sediment that is held in the water column by turbulence) (Fig. 1). Sedimentation in reservoirs causes a progressive reduction of dam impoundment capacity, and creates serious problems for water management, especially near dam outlets. Water quality in storage can also be degraded, due to phenomena such as eutrophication.

Figure 1. The Segre River debouching into the Ribarroja reservoir, downstream the Mequinenza Dam, during a small flood (photograph by the author, June 2001).

Figura 1. El río Segre desembocando en el embalse de Ribarroja, aguas abajo de la presa de Mequinenza, durante una pequeña crecida (fotografía del autor, junio de 2001).

Dams are also responsible for changes in river morphology and ecology downstream, their nature depending upon characteristics of the original and altered flow regimes and sediment loads. Dams disrupt the continuity of the river system and, especially its sediment load, interrupting the conveyor belt of sediment transport. Dams release sediment-starved, or "hungry water" to downstream reaches, which may transport sand and gravel downstream without replacement from upstream, resulting in coarsening of the surface layer termed 'armouring', and because the excess energy may erode the river bed, resulting in incision, and undercut banks, thereby causing widening. Effects of hungry water on river channels can cause dramatic changes on river ecology, such as loss of spawning gravels, and damage to bridges and other infrastructure (Kondolf, 1997).

In addition, dams diminish the magnitude of floods, which transports the majority of sediment, and reduce sand supply to coastline and deltas. Under such conditions, beaches can become undernourished, shrink, and coastal and delta erosion may be accelerated (Inman, 1976). In the delta regions, the equilibrium between fluvial and marine processes is disrupted. There, sediment deposition is no longer in balance with coastal erosion. The erosion of the Nile Delta (150 m per year), 1000 km downstream of the Aswan High Dam demonstrates the importance of sediment supply from the upper catchment. Other examples can be followed elsewhere (e.g. Brownlie and Taylor, 1981). Beach nourishment with imported sediment dredged from reservoirs and harbours has been implemented along many beaches in southern California (Inman 1976, Allayaud 1985, Everts 1985). However, the high costs of transportation, sorting for the proper size fractions and cleaning of contaminants of dredged materials, as well as the difficulty in securing a stable supply of material make these options infeasible in many places (Inman, 1976).

To integrate considerations of fluvial sediment supply in the maintenance of coastal beaches into the existing legal framework, a system of 'sand rights' analogous to water rights, has been proposed (Stone and Kaufman, 1985).

1.3. Effects of instream gravel mining

Instream gravel mining is, together with dams, the main cause for sediment deficit in many rivers. Sand and gravels are used for construction purposes and they are derived primarily from alluvial deposits, most times directly from the river bed. Instream mining directly alters the channel geometry and bed elevation, while disrupting the continuum of sediment downstream. Main effects of gravel mining are *in situ* but also downstream (Kondolf, 1997):

- Channel incision and bed coarsening, in a similar way that a dam disrupts the preexisting balance between sediment supply and transporting capacity
- Undermining of structures, as direct effect of channel incision and lateral channel instability (Fig. 2)
- Destruction of fish habitat in the mining reaches and downstream, by modification of pool-riffle distribution and alteration of intergravel flow paths
- Lack of sediment supply to coastline and delta areas. Due to the high of cost of transportation many aggregate supply operators concentrate their activities in alluvial zones near the areas of consumption, typically near cities and tourist centres

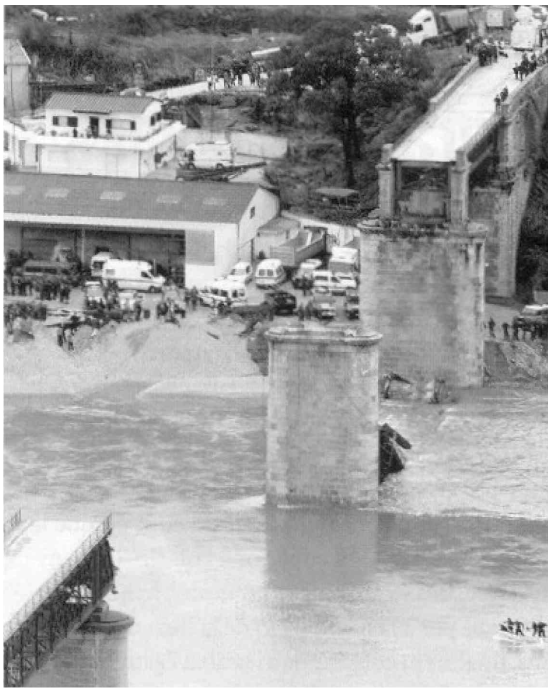

Figure 2. Bridge collapse in the Duero River upstream Castel de Paiva, 4th March 2001
Figura 2. Derrumbe de un puente sobre el río Duero aguas arriba de Castel de Paiva, 4 de marzo de 2001.

1.4. Methodological issues and management strategies

Assessment of sediment deficit in regulated and mined rivers requires long-term monitoring programmes, which many countries do not have. Instead, sparse data have to be used to evaluate sediment budgets in regulated and mined rivers.

Ironically, sediment got trapped within reservoirs while rivers are profoundly altered downstream by gravel mining and coastline and deltas suffered from an intensive sediment deficit. Only few places, such as Israel, California and Taiwan have undertaken official pilot programmes for a better understanding of the degree of river alteration created by those activities, as the basis for management strategies.

Sand and gravel are commercially mined from some debris basin in Los Angeles and from Rollins Dam. In Taiwan, virtually all dams are mined for construction aggregate (Kondolf, 1997). In Israel, the Shikma Reservoir is mined in its upper part to produce sand and gravel for construction aggregate and in its lower to produce clay for use in cement and bricks (Laronne, 1995). In the Pyrenees, the delta of the Talarn Reservoir in the Noguera Pallaresa River is often mined for aggregate (0.6 hm^3 have been extracted from 1992 to 2001). Few examples are reported on artificial supply of sediment downstream dams to restore fish habitat (Sacramento River) (Buer, 1994) and to regain sediment yield to coastline (South California) (Inman, 1976).

2. Sediment deficit in regulated rivers of NE Spain

2.1. General considerations for the Mediterranean and Spain

Mediterranean-climate rivers are highly variable in flow and sediment load (Conacher and Sala, 1998). The high variability in runoff means that large, infrequent floods tend to carry a great percentage of runoff than would be the case in a comparably-sized humid climate river, and moreover, these floods carry proportionately higher sediment loads. Channel processes in the Mediterranean (and other semi-arid regions) are dominated by infrequent, episodic events much more than in comparable humid-climate rivers (Wolman and Gerson 1978, Hecht 1994).

In Mediterranean-climate regions, water availability and demand are out-of-phase. Precipitation and runoff occur (almost exclusively) in the fall and winter, while plants are dormant and demand for irrigation (and often hydroelectric generation) is lowest. Thus, seasonal and inter-annual water storage is needed to meet the basic needs of human populations, to support industrial-scale agriculture, and often to satisfy public demand for flood control. As a result, Mediterranean-climate rivers tend to be more highly regulated than humid climate rivers of comparable size. For example, Spain (whose climate is Mediterranean except in the north-western provinces) has more dams than any other country in Europe and 2.5% of the population of dams of the world. Spain is first among European countries as a dam-building nation, and fourth in the world after China, India and USA. The construction of dams to alleviate water shortages began in Roman times. Today there are almost 1,200 large dams in Spain, of which 1,165 are in operation and 31 under construction. Dams in Spain have a total combined capacity of 54.6 km^3, with 98% of storage capacity in 300 reservoirs (Fig. 3).

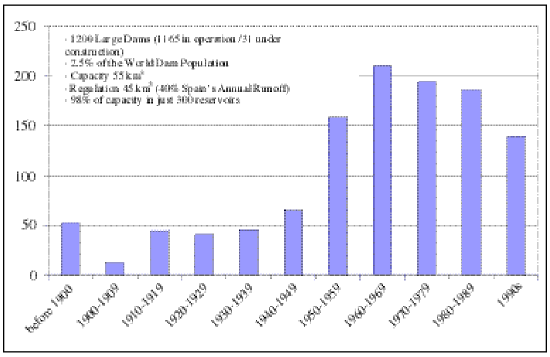

Figure 3. Dam Commissioning in Spain by Decade (Source: ICOLD World Register Dams, 1998).

Figura 3. Distribución por décadas de la construcción de embalses en España (Fuente: ICOLD World Register Dams, 1998).

Part of the total reservoir storage capacity is lost due to sedimentation. Surveys carried out in 121 reservoirs considered to face silting problems and representing 50% the area covered by reservoirs in Spain, indicate that 6% have suffered a reduction in capacity of 50%, while 80% of them have lost less than 20% of capacity (Fig. 4)

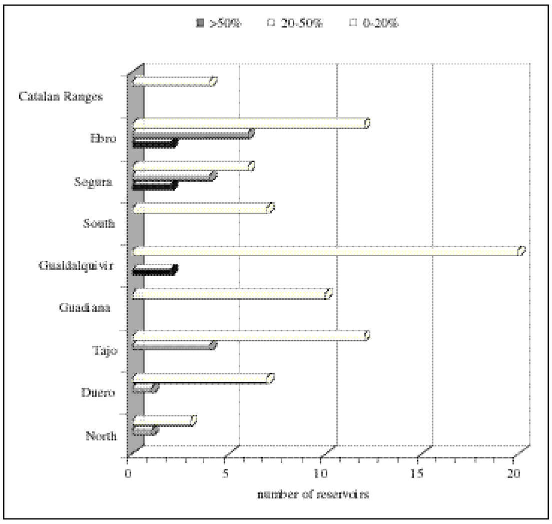

Figure 4 Reservoirs in Spain experiencing capacity losses (in %) due to sedimentation (data source: Avendaño *et al.*, 1997).
Figure 4. Embalses con pérdida de capacidad (en %) por sedimentación en España (fuente: Avendaño et al.*, 1997).*

(Avendaño *et al.*, 1997). Assuming that the remaining reservoirs have no significant silting problems, mean weighted reduction for dams in Spain can be estimated around 10%. Dams built up during the 20th century in Spain are, on average, 35 years old. Combining these two figures, we obtain a mean annual reduction of reservoir capacity of 0.3%, below the world mean of 1%, giving an estimated total sedimentation of around 170 hm^3 per year. As a consequence, mean life expectancy for reservoirs in Spain is around 250 years from its date of construction. According to data from Avendaño *et al*. (1997), at least 11% of reservoirs in Spain are already experiencing acute silting problems, but many more will face them within the next decades, if appropriate environmentally sounded steps are not taken (Fig 5).

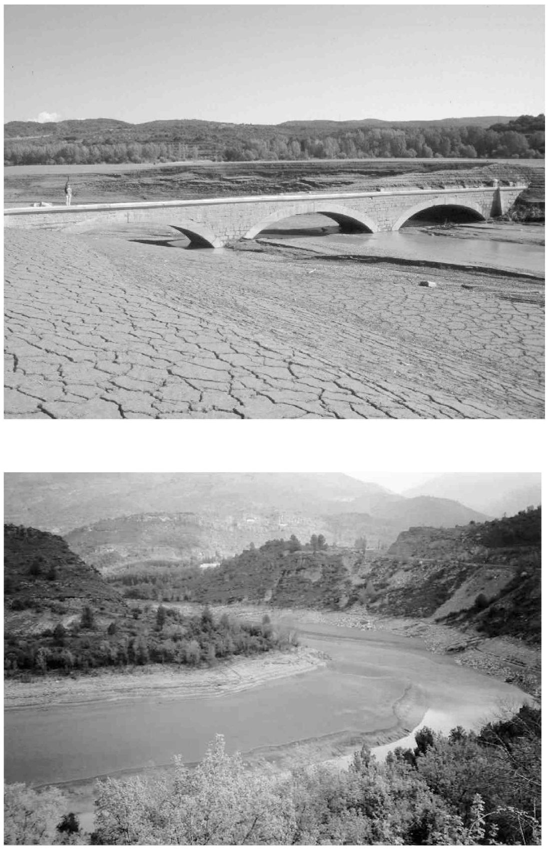

Figure 5. Above, silt (76%) and clay (19%) sedimentation in the Barasona reservoir (Ésera and Isábena Rivers, Ebro basin). Below, sedimentation in the Camarasa reservoir (Noguera Pallaressa River) (photographs by the author, April and June, 2001).
Figura 5. Arriba, sedimentación por limos (76%) y arcillas (19%) en el embalse de Barasona (ríos Ésera e Isábena, cuenca del Ebro). Abajo, sedimentación en el embalse de Camarasa (río Noguera Pallaressa) (fotografías del autor, abril y junio de 2001).

2.2. The Ebro River

One hundred eighty-seven reservoirs regulate 57% (7,700 hm^3) of the Ebro River's total mean annual runoff. This is a much higher rate of impoundment than typically encountered in more humid regions. For example, if we consider similarly sized German rivers, reservoir capacity is from 5 to 18% of the annual runoff on the Elbe, Rhine and Wesser Rivers (P. Ergenzinger and C. de Jong, Freie Universität Berlin, personal communication). Forty dams, impounding 22% of the annual runoff, are owned and regulated by the state. Most reservoirs are located in the central and the upper reaches of the tributaries at a mean elevation of about 700 m, ranging from 2,189 m (Llauset Reservoir on the Noguera Ribargorçana) to 40 m (Flix Reservoir on the mainstem Ebro). Only three major streams, the Ega, Jiloca and Valira, are not regulated. None of the major dams were built for flood control, although the sheer volume of impoundments is likely to affect flood magnitude. Diverted water is used mainly for hydropower production (60,000 hm^3/year running 240 hydropower stations and producing 6,700 Gwh/year), for irrigation purposes (6,310 hm^3/year), cooling water for nuclear plants (3,350 hm^3/year), and for industry and domestic use by almost 3 million people (313 hm^3/year) (www.oph.che.es).

Virtually all dams were constructed during the 20th century, with 67% of reservoir capacity built in the period 1950-1975, when 5200 hm^3 of water was impounded – an average impoundment rate of more than 1.5% of the annual runoff per year. Most reservoirs in the Ebro basin are small. Of the one hundred and forty-two reservoirs larger than 10,000 m^3 (0.01 hm^3) capacity, two thirds have capacities above 1 hm^3, 18% above 50 hm^3 and 3% above 400 hm^3. The twenty-four reservoirs with capacity between 50 and 500 hm^3 have a total storage capacity of 4,200 hm^3, equivalent to 30% of the total annual runoff and, thus, play an important role in regulating flows in the basin. The Ebro Dam on the Ebro headwaters in the Cantabrian Ranges has a capacity of 175% of annual runoff, the largest capacity relative to runoff in the catchment.

Dams impound water but also trap most sediment circulating in the basin. Using the same sedimentation rates as for the whole of Spain, but taking into account that reservoirs in the Ebro basin are, on average, older (50 years), mean annual reduction of reservoir capacity would be 0.2%, giving an estimated total annual sedimentation of 15 hm^3. The same sedimentation rate (0.2%) can be obtained from data reported by Sanz *et al*. (1999) for seventeen reservoirs representing 50% of basin total impoundment capacity and experiencing silting problems. Sediment retained in reservoirs along the Ebro basin is composed mainly by silt (62%), followed by clay (25%) and sand (13%) (Sanz, 1998).

Some reservoirs are already full of sediment (e.g. Pignatelli in the Ebro main stem, constructed in 1790 with an original capacity of 1 hm^3 and Escuriza in the Martín River, constructed in 1890, with an original capacity of 6 hm^3). In others, sedimentation has been recognized as a problem: e.g. Terradets on the Noguera Pallaressa, constructed in 1935, with an actual capacity of 8 hm^3 from an original of 23 hm^3.

On few occasions, sediment has been sluiced during low flows to clean out reservoirs (e.g. Santa Anna and Barasona in the Noguera Ribargorçana and the Ésera Rivers, respectively). Despite substantial environmental impacts, further sluicing is proposed, such as a plan to sluice sediment from Oliana reservoir on the Segre downstream to the Rialb reservoir.

According to data from Bayerri (1935) and further estimates by Nelson (1990) the annual sediment contribution of the Ebro to its delta at the beginning of the 20th century was around $15 \cdot 10^6$ tonnes. Most of that sediment was carried in suspension as indicated by mean concentrations around 1 g l^{-1}, rising to 10 g l^{-1} during floods. As generally assumed for alluvial rivers, coarse fraction (sand to gravels and cobbles) comprise no more than 10% of sediment transport and, thus, between 1 and 1.5 10^6 t/y were carried as bedload. This data agrees with calculations by Guillén *et al*. (1992).

At the time Mequinenza and Riba-roja dams were set in operation (1966 and 1969, respectively) annual sediment discharged to those reservoirs was already reduced to $6 \cdot 10^6$ tonnes, according to bathymetric data reported by Avendaño *et al*. (1997), mostly due to upstream sediment trapping. This value gives a mean annual capacity reduction of 0.4%, in contrast with 0.2% estimated for the whole basin over the century. This fact can be explained by the wet period after which sedimentation surveys were conducted by CEDEX. Therefore, a reliable estimation of total sediment inflow into those reservoirs could be around $3 \cdot 10^6$ t/y, of which still 90% was transported as suspended load ($2.7 \cdot 10^6$ t/y) and 10% as bedload (300.000 t/y). This value agrees with calculations on bedload transport capacity reported by Guillén *et al*. (1992) and Vericat *et al*. (2002). Palanques and Drake (1990) reported a total sediment load entering the Mequinenza and Riba-roja system of $0.5 \cdot 10^6$ t/y, while Sanz *et al*. (1999) calculated $1 \cdot 10^6$ t/y from suspended sediment samples.

Sediment trapping efficiency for suspended sediment of Mequinenza and Riba-roja reservoirs has been estimated around 90%, following the method by Brune (1953). Sanz reported a mean release of 263,000 t/y. This value represents 10% of upstream sedimentation reported by CEDEX and modified in this paper to a mean of $3 \cdot 10^6$ t/y. Guillén *et al*. (1992) estimated the amount of 120,000 t/y of sediment discharged into the sea, which would include 50,000 t/y to 100,000 t/y released from reservoirs plus some sediment eroded from river channel and banks.

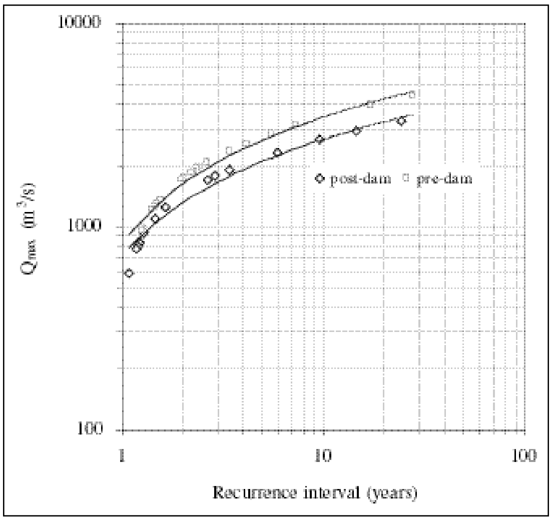

Figure 6. Reduction of the annual maximum floods in the lower reach of the Ebro River (Tortosa), downstream the Mequinenza and Ribarroja reservoirs (Batalla *et al.*, 2003).
Figura 6. Reducción de la magnitud de las avenidas máximas anuales en el tramo bajo del río Ebro, aguas abajo de los embalses de Mequinenza y Ribarroja (Batalla et al.*, 2003).*

All bedload is trapped by reservoirs. The Ebro River does not receive coarse fractions from upstream Mequinenza and Riba-roja dams, but partially keeps its bedload transport capacity since floods have not been dramatically reduced (Fig. 6). Bedload capacity has been estimated around 150,000 t/y (Vericat *et al*., 2002), sediment that is entrained from bed and lateral deposits, and deposited at the river lowermost reaches, already in the delta plain. However, for long periods of time, especially in the nineties, the river has not reached the critical discharge for bedload entrainment, stressing the deficit in sediment transport and causing changes in river morphology (Vericat *et al*., 2002) (Fig. 7). In addition, over recent years, the river-bed has been almost continuously dredged at a rate of 40,000 tonnes per year to ensure the navigability of the river for tourism purposes, destroying fish habitat and contributing to the disequilibrium of the river's sedimentary system.

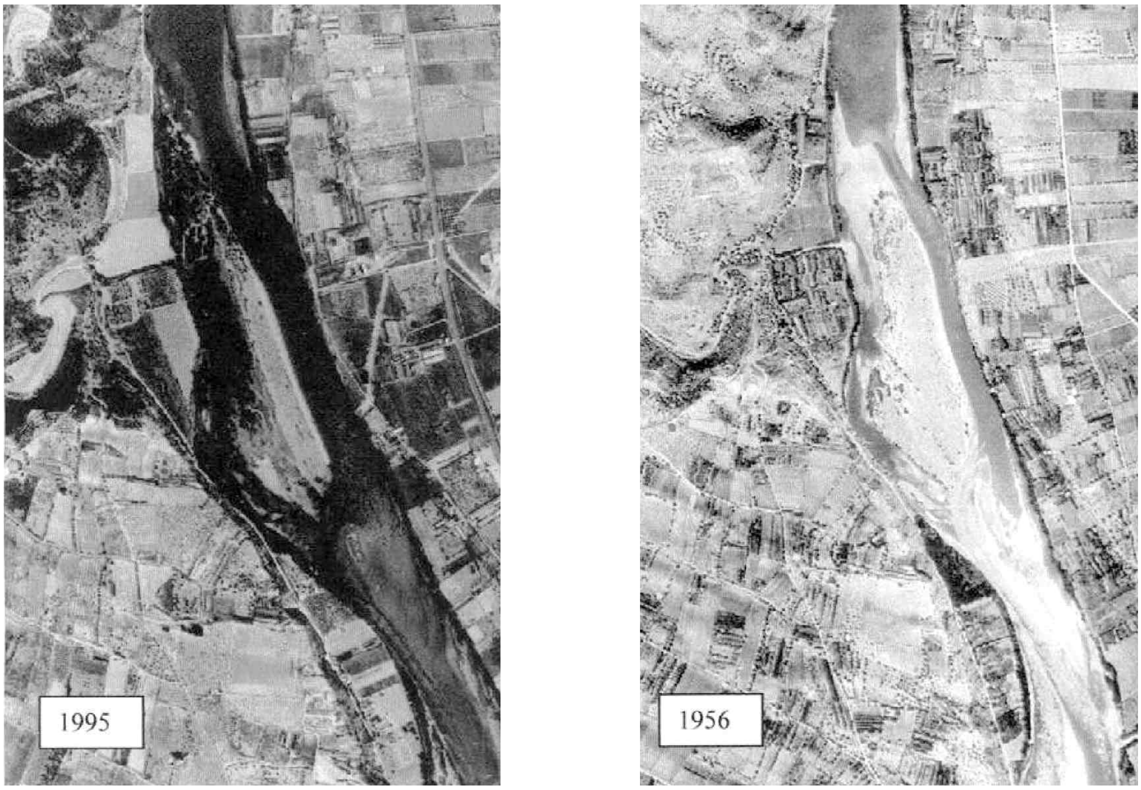

Figure 7. Vegetation encroachment downstream in the Ebro River due to the lack of floods (Vericat & Batalla, 2003).
Figura 7. Colonización por vegetación de ribera debido a la falta de avenidas de una barra activa en el tramo bajo del río Ebro (Vericat & Batalla, 2003).

Altogether, of the order of 200,000 t/y are still probably discharged from the Ebro River to the sea, 1.5% of what it was delivered at the beginning of the 20th century. Lack of sediment nourishment due to large dam construction and reduction in sediment transport capacity can be identified as the main reason for the retreat of the Ebro delta, which has been observed since the seventies.

River adjustment downstream of dams can be approached by means of the qualitative expression by Lane (1955), which indicates that

$$q_s D \qquad q i$$

where q_s is solid load, D is sediment size, q is water discharge and *i* is slope. According to that, the Lower Ebro would compensate its severe loss in sediment load by increasing slope and, thus, erosion of the river channel, and rate of sediment transport. Rate of channel degradation is estimated to be around 0.03 m/y, which would mean 1 meter of incision since the Mequinenza and Riba-roja are in operation. Effects such as channel incision and bed armouring are still not completely visible in the field, since the river can erode its margins as well (Fig. 8). The increase of bedload within the total load (from 10% to 50%) would also slowly move the river towards that new equilibrium.

2.3. Rivers in the Catalan Coastal Ranges and the Eastern Pyrenees

Eight dams in rivers of the Catalan Coastal Ranges and the Eastern Pyrenees capture almost half of the water yield (Fig. 9). The Ter and Cardener rivers, the latter the main tributary of the Llobregat, are the most strongly impounded rivers in the region, with the Sau and Susqueda Dams capturing 107% and La Llosa de Cavall and Sant Ponç capturing 100% of annual water yield, respectively. All of them were primarily constructed for domestic and industrial water supply. Only two major streams, Tordera and Fluvià are not regulated.

Most reservoirs are located to capture most of the runoff generated at the basin headwaters (5,000 km^2 of land upstream reservoirs), but they not only capture water but also most sediment that, otherwise, would be transported downstream. Using the same rates as for the Ebro basin (0.2%), estimated annual sedimentation in reservoirs of the Catalan Coastal Ranges would be around 1.4 hm^3, most of which would otherwise arrive to the coastline. This value agrees with the 100 t/km^2 estimated by Batalla and Sala (1995) as mean annual sediment yield of rivers in Catalonia. This figure yields an average annual sediment contribution of the order of 1 t/ha, indicating low erosion rates upstream of

Figure 8. Side erosion of the Ebro River downstream the Mequinenza-Ribarroja reservoirs (photograph by the author, June 2001).
Figure 8. Erosión lateral en el cauce del Ebro aguas abajo de las presas de Mequinenza y Ribarroja (fotografía del autor, junio de 2001).

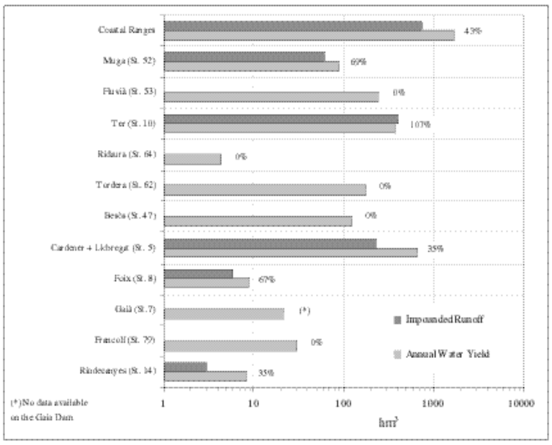

Figure 9. Mean annual water yield and impounded runoff in rivers of the Catalan Coastal Ranges and Eastern Pyrenees, with indication of percentage of impoundment capacity over water yield (data source: Junta d'Aigües, 1995).
Figura 9. Aportación hídrica annual y % de agua embalsa - da en ríos de las Cordilleras Costeras Catalanas y el Pirineo Oriental (fuente: Junta d'Aigües, 1995).

such dams. To make the conversion from volume to mass, a mean density of 1.1 t m^{-3} for sediment in Spanish reservoirs can be applied (Sanz *et al*., 1999), a value in the range of that reported by Morris and Fan (1997) but lower than 1.6 t m^{-3} of Vanoni (1975). No official data has been reported in Catalonia on reservoir sedimentation yet.

Around 60% of such sedimentation (0.9 hm^3) would occur in reservoirs located in the Ter River, mainly in the Sau reservoir, while more than 30% (0.5 hm^3) would take place in dams of the Llobregat River, the La Baells dam being the most affected, with a reduction of 20% of its capacity already in 1988 (Fig. 10). Sedimentation problems are especially acute in the Foix reservoir, where at least half of dam is full of sediment (Catalan Water Authorities, personal communication).

3. Sediment deficit due to gravel mining in rivers of NE Spain

Sand and gravel mining is, together with dams, the main cause of historical sediment deficit in rivers and coastline in Spain. Fluvial mining has taken place under almost no control up to now, creating a huge sediment unbalance in many rivers, most of them also regulated, thus with an upstream sediment deficit.

Annual consumption of aggregate in Spain and Catalonia is estimated at around 7 tonnes per person, the second largest natural resource used after water, (www.aridos.org, www.gremiarids.com), at a mean value in the market of 7€ per tonne. Until the nineties,

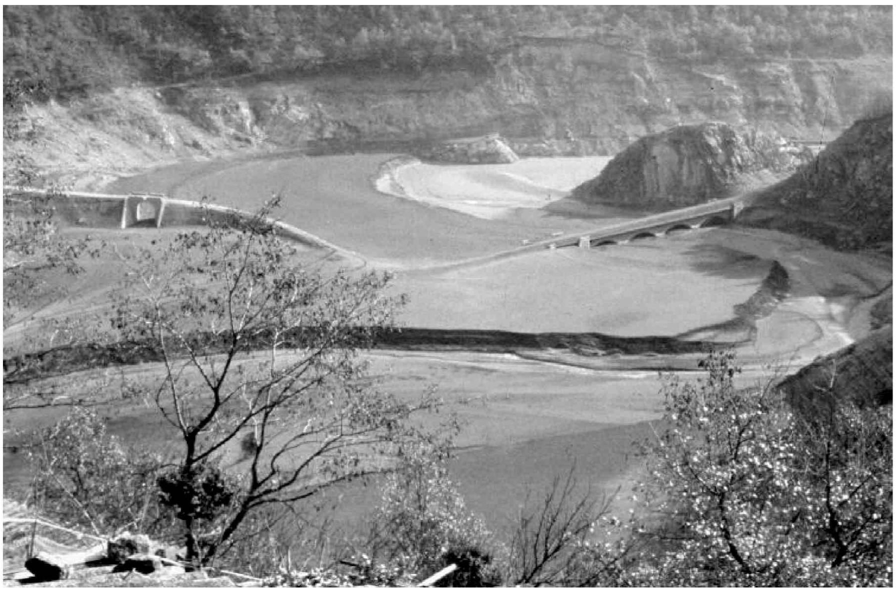

Figure 10. Sedimentation in the La Baells reservoir, Upper Llobregat River (photograph by the author, January 2002).
Figura 10. Sedimentación en el embalse de La Baells, Alto Llobregat (fotografía del autor, enero de 2002).

the majority of that aggregate was obtained directly from river deposits. In the case of the Ebro, the Catalan Coastal Ranges and the Eastern Pyrenees that meant an annual extraction of several million tonnes, an important part of the Ebro basin's annual bedload yield and, at least, one order of magnitude higher than the annual bedload yield in rivers of the Coastal Ranges.

Gravel mining has been particularly intense in some tributaries of the Ebro, which already showed a severe sediment deficit due to upstream regulation. Examples of brutal mining can be seen elsewhere in the Segre mainstem and its tributaries such as the Noguera Pallaresa, the Noguera Ribagorçana and the Ribera Salada, in which the sediment by volume extracted within the last twenty years is two hundred times higher than the annual mean bedload yield (ca. 2000 t/y) (Fig. 11 and Fig. 12).

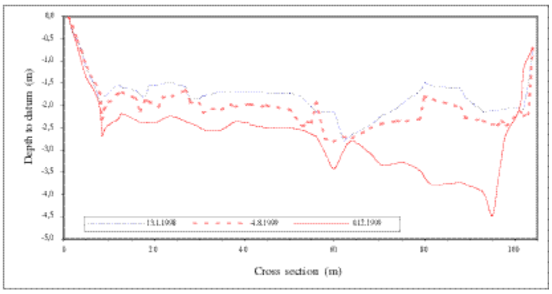

Figure 12. Recent evolution of a monumented cross section in the Ribera Salada gravel mining zone (mean incision: 1 m; maximum incision: 3.5 m; section lost: 80 m^2; extraction length: 500 m; estimated extraction 40000 m^3).

Figura 12. Evolución reciente de una sección de control en la zona de extracción de la Ribera Salada (incisión media 1 m; incisión máxima: 3,5 m; sección perdida: 80 m^2; tramo de extracción: 500 m; extracción estimada: 40000 m^3).

Figure 11. Intensive gravel mining in the Ribera Salada, a tributary of the Segre River. Ecological effects can be viewed: (above) complete destruction of river morphology and ecosystem and, (below) groundwater overdrafting due to extensive mining down to the bedrock, exposing the water table (photographs by the author, June and November 2001).

Figura 11. Extracción intensiva de áridos en la Ribera Salada (cuenca del Segre). Los efectos ecológicos que se observan son: (arriba) destrucción completa de la morfología y del ecosistema fluvial asociado, (abajo) sobredrenaje del acuífero debido a la extracción de gravas hasta la roca madre (fotografías del autor, junio y noviembre, 2001).

The Siurana River, the main downstream tributary of the Ebro River suffers from intensive gravel mining downstream of the Siurana Dam (Fig. 13) and especially in its lowermost reach, reducing to virtually nothing its sediment contribution to the Ebro mainstem. This fact, between other environmental and economic impacts, accentuates the sediment deficit of the Lower Ebro.

One of the most dramatic examples of wild gravel mining in the Catalan Coastal Ranges can be followed in the unregulated Tordera River (970 km^2). There, around $5 \cdot 10^6$ tonnes of sand and gravel were extracted during the decades of the sixties and seventies until 1987, when mining was prohibited. This means ten times more than the annual sediment yield of the Tordera River, including both suspended and bedload (Rovira *et al.*, 2002). Fluvial sediments were converted to aggregate for construction in the Costa Brava area during the rapid growth of tourism during those decades. Consequences of intensive gravel mining were several, but includes massive destruction of river ecosystem, channel incision with the consequent undermining of several bridges (Fig. 14), some of which collapsed, groundwater overdrafting, and severe lack of sediment nourishment to the delta and beaches from Blanes to Barcelona.

Damage to bridges and other infrastructure due to gravel mining is not directly incorporated in the price of aggregate. In the case of the Tordera ratio between cost of bridge reconstruction and rein-

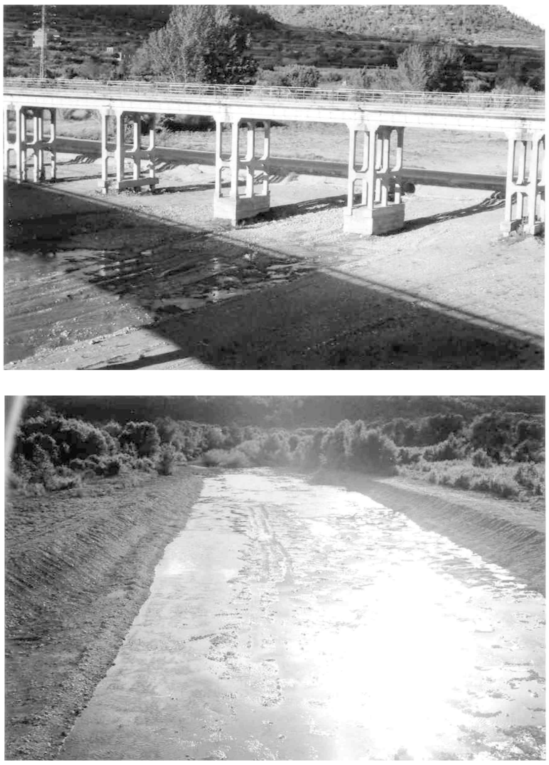

Figure 13. Intensive gravel mining and subsequent bridge underming in the Siurana River, upstream its junction with Ebro River. Even during low flows, water flows upstream from the Ebro (photograph by the author, June 2001).

Figura 13. Minería de gravas intensiva y socavamiento de puente en el río Siurana, aguas arriba de su confluencia con el río Ebro. Incluso durante caudales bajos, el agua fluye Siurana arriba desde el Ebro (fotografías del autor, junio de 2001).

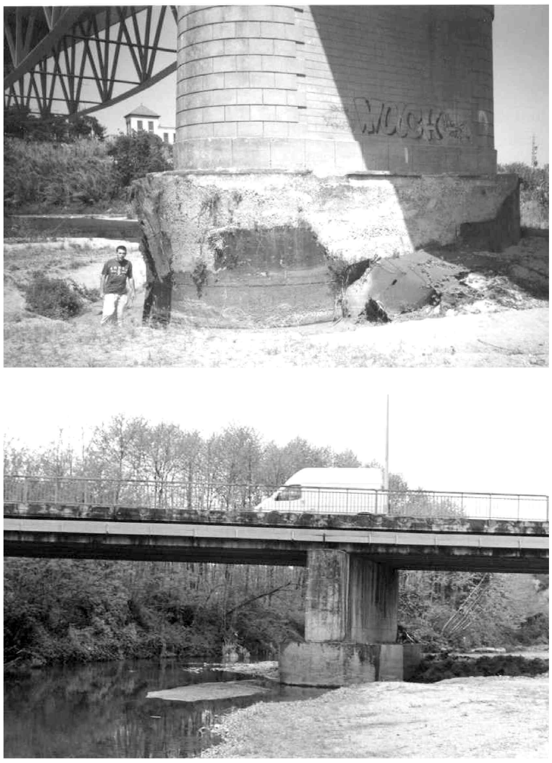

Figure 14. The N-II road bridge in the Lower Tordera (above) and the A-7 access road bridge in the Tordera near Hostalric (below) illustrate river-bed incision due to gravel mining from the fifties (photographs by the author, June 2001).

Figura 14. Los puentes de la N-II cerca del pueblo de Tordera (arriba) y de acceso a la A-7 cerca de Hostalric (abajo) ilustran la incisión del lecho del río como consecuencia de las extrac - ciones de áridos ejecutadas desde los años cincuenta en la Tordera (fotografías del autor, junio de 2001).

forcement and mass of sand and gravel extracted gives estimation of the order of 2 to 4€ per tone, closed to the 5 US$ of post-failure public investment per tonne of gravel estimated in the San Benito River in California (Kondolf, personal communication).

Downstream reaches of the Llobregat River were also intensively mined during the fifties and the sixties. At that time, there was a big demand of aggregate for construction linked to the fast economic growth of the metropolitan area of Barcelona. Besides destruction of river ecosystems and lack of sediment supply to the delta, many infrastructures were undermined, as was the case of the Carlos III bridge in Molins de Rei, which collapsed during a flood in 1971 (Fig. 15).

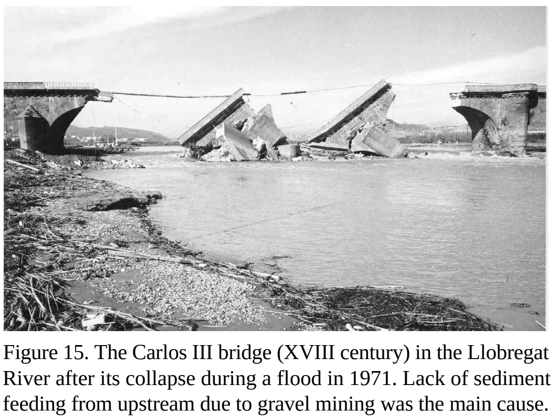

Figure 15. The Carlos III bridge (XVIII century) in the Llobregat River after its collapse during a flood in 1971. Lack of sediment feeding from upstream due to gravel mining was the main cause.

Figura 15. El puente de Carlos III (siglo XVIII) en el río Llobregat después de su derrumbe durante una crecida en 1971. La falta de aporte de sedimento debido a las extracciones masivas de áridos aguas arriba fue la causa.

4. Prospects and conclusions

Deficit of sediment in rivers and coastlines is mainly the consequence of the unbalance within the fluvial system caused by dams and instream gravel mining. Those activities disrupt the continuum of sediment from river headwaters to deposition zones, producing severe alterations of river hydrology, morphology and ecology, and damaging infrastructures. In particular, coastlines and deltas are amongst the most damaged ecosystems due to the lack of sediment feeding. This review has shown examples of rivers with important sediment deficits in NE Spain, including the Ebro.

Sediment is flowing naturally through the drainage network. Any disruption to its continuity may create downstream environmental problems. Any comprehensive attempt of sediment management in river systems must be based on that fact. Long-term programmes need to be implemented to monitor sediment transport in river basins, in order to assess its deficits. But short-term actions can also be undertaken, such as:

a) strict prohibition of gravel mining in heavily unbalanced rivers, especially in those reaches downstream dams
b) aggregate recycling, especially for low quality applications
c) sediment-pass through in reservoirs only during high flows
d) periodical removal of sediment from reservoirs
e) artificial sediment nourishment downstream of dams to feed flushing flows in rivers facing severe ecological problems, like loss of fish habitat.

Finally, the cost of sediment-starvation related problems should realistically be estimated and incorporated in the price of products (aggregate, electricity), instead of being masked with public resources.

Acknowledgements

This paper is the synthesis of two years of investigation, starting when the author was a visiting researcher at the University of California, Berkeley, thanks to a grant funded by the Gaspar de Portolà Programme, Generalitat de Catalunya. The initial report was partially prepared within the framework of the EUROSION project (European Commission 2002-2003). Work has benefited from fruitful discussions with G. Mathias Kondolf (UC Berkeley) and J. Carles Balasch (University of Lleida). Albert Rovira and Damià Vericat (University of Lleida) and Oscar Alisedo (Forestry Institute of Catalonia) assisted during fieldwork and supplied data as well. Comments by Rafael Cobo (CEDEX) and an anonymous reviewer have improved the final version of the paper.

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Recibido 10 de abril de 2003.
Aceptado 20 de mayo de 2003.