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Changes in fluvial sediment storage from aerial photograph analysis (river Narcea, Northern Cantabrian Range)

Estimación de cambios en el almacenaje de sedimento fluvial a partir del análisis de fotografías aéreas (Río Narcea, Norte de la Cordillera Cantábrica)

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Abstract

Work aims at providing estimates of volume changes in active sediment storage for lower River Narcea (NW Iberian Peninsula) during the last six decades, through surface changes, identified from aerial photographs taken at different dates. A five step procedure was followed: 1) Georreferencing of aerial photographs. 2) Mapping of active channel surface and fluvial bars, on each aerial photo. 3) Aerial photography correction regarding water flow stage and channel width. 4) Assumption of a thickness for active sediment layer. 5) Estimating sediment volume changes. Estimated changes have been linked to human interventions on the studied reach of channel (embankments and dam). A reduction in the volumes of active gravels is observed, mainly linked to the abandonment of formerly active deposits and its colonization by vegetation.

Keywords: channel morphology, channel storage, bedload transport, aerial photograph, GIS.

Resumen

Este trabajo tiene como objetivo la estimación de las variaciones de volumen de sedimento experimentadas por el bajo Narcea (Asturias, NO Península Ibérica) en las últimas 6 décadas, a partir de las variaciones en superficie, identificables sobre fotografías aéreas de la zona tomadas en fechas diferentes. Se han seguido los siguientes pasos: 1) Georreferenciación de las fotografías aéreas. 2) Cartografía de la superficie ocupada por la mancha de agua y por barras fluviales activas. 3) Corrección de los valores de superficie. 4) Asunción de un valor para el espesor del sedimento móvil y para la porosidad. 5) Estimación de los cambios de volumen. Las variaciones obtenidas han sido relacionadas con las intervenciones antrópicas sobre el tramo de río estudiado (canalizaciones y presa). Se observa una reducción en los volúmenes de gravas expuestas debido principalmente a su abandono y colonización por vegetación.

Palabras clave: Morfología de canal, transporte sedimentario, carga de fondo, fotografía aérea, S.I.G.

1. Introduction

Rivers store sediment along its course in channel bed and bars, and floodplains. Transport processes are able to mobilize this sediment, which is transported and/or deposited downstream. Changes in sediment balance between transport capacity and sediment supply through time are reflected in volume changes in the storage of active sediment (Martin and Church, 1995; Werritty, 1997; Ham and Church, 2000). In response to changes in the volumes stored, alluvial channels are subject to modifications in channel pattern and bar distribution, as they response to the variations in storage and input of sediment (Martin and Church, 1995; Lane and Richards, 1997; Ham and Church, 2000). These processes are related with sediment transport dynamics and rate variations, which can be induced by several causes: extreme floods (Werritty, 1997), natural changes in the hydrologic response of the river or in the basin hydro-climatology (Milhous, 2005; Walling, 2009), embankment works (Simon, 1989; Surian, 1999), dam construction (Kondolf, 1997; Wellmeyer *et al*., 2005; Vericat and Batalla, 2006; Vericat *et al*., 2006) and/or land use changes (Kuhlne *et al*., 1996; Rinaldi and Simon, 1998).

Different ways to estimate and measure sediment transport have been developed. Some imply a direct measurement, as the use of samplers (Helley-Smith, 1971; Emmett, 1980), traps (Reid *et al*., 1980) or tracers (Hassan *et al*., 1984). Another way is the indirect or morphological approach, based in the existent relations between changes in channel morphology and sediment transport (Ham, 1996; Martin and Church, 1995; Ashmore and Church, 1998; Ham and Church, 2000; Ham, 2005). In the later, aerial photographs have been widely used for geomorphological purposes, particularly to identify changes in fluvial environments (Lewin and Hughes, 1976; Surian, 1999; O'Connor *et al*., 2003; Hughes *et al*., 2006); and also, to explore sediment transport behaviour in gravel-bed rivers (Ham, 1996; Martin and Church, 1995; Ham and Church, 2000).

This paper presents a description of changes in active sediment volume over the period 1957-2007 in the lower reach of a mountain river located in the northern side of the Cantabrian Range. With 'active sediment' we mean the sediment placed in the bankfull channel and located in active bars; we also include bankfull margins, not stabilized by dense vegetal cover. This sediment was considered to be ready for transport by frequent (annual) flood events. Volume changes were estimated through the identification of surface changes in the active channel and active bar deposits, mapped using sequential aerial photographs.

2. Study site

The study reach covers the lowest 20 km of the River Narcea (NW Spain). The river drains a catchment of 1800 km^2 towards the northern side of the Cantabrian Range (Figure 1). Elevations range from roughly 200 m a.s.l. to near 2000 m in the upper parts. Climate is Atlantic with an average annual precipitation of 1100 mm, and a vegetation cover dominated by oak, chestnut tree and pine forest. The lithology comprises a diversity of Paleozoic

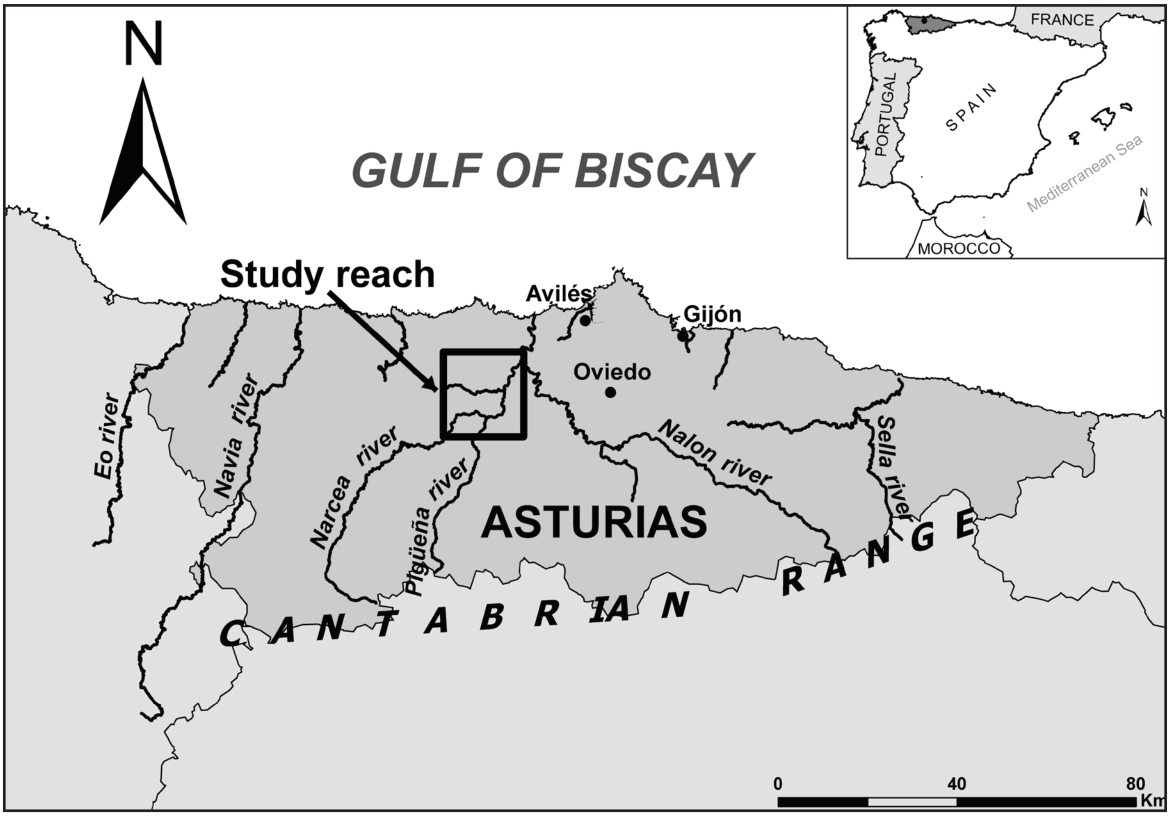

Figure 1. Study site location (Northwestern Spain).
Figura 1.Localización del área de estudio (NW de España).

sedimentary rocks, predominating siliciclastic lithologies (quartzarenites, shales, slates) in the western side and siliciclastic and calcareous ones in the Pigüeña River subbasin. The origin of relief is related to Alpine tectonics contemporaneous to the compressive tectonic episodes which uplifted the Pyrenees. Dominant geomorphic processes include fluvial, glaciar and slope movements (Farias and Marquínez, 1995).

The River Narcea has an average daily discharge of 53 m^3s^{-1}. Bankfull discharge reaches 250 m^3s^{-1}, roughly corresponding to the flood with a recurrence interval of 1.5 years. Its hydrological regime is dominantly pluvial. Principal tributaries of lower Narcea are the Pigueña and the Nonaya rivers (Figure 2). Grain size of river bed is dominantly gravelly: 90% of the bed sediment has a size larger than 2 mm and the D50 is 45 mm.

The Narcea meets the River Nalon at the location of Forcinas (Figure 2). The confluence is located 10 km upstream of the mouth where the Nalon debouches to the Gulf of Biscay. The Narcea develops in its lower reaches a 400 m wide floodplain characterized by a very intense geomorphic activity, with dominant flood frequencies of 10 years, in some cases lower than 5 years (INDUROT, 2004). During the time period analyzed (1957-2007), three major floods occurred, in 1959, 1983 and 1998, along with several flood events of lower magnitude.

The lower Narcea has been affected by human interventions of two different kinds: (a) construction of the *La Barca* hydropower dam, finished in 1966; (b) river embankment works carried out during the last 60 years (Fernandez *et al.*, 2006). The main engineering works of the later type includes:

- La Defensa lateral dyke finished in 1955.

- Quinzanas' channelization works, the first of them carried out in 1984 and the latest in 1992.

- Embankments at Cornellana and at the Nalon-Narcea confluence (Forcinas), constructed in 1994.

There are two main gauging stations in the river. One is located upstream of the *La Barca* Dam (Corias gauge station) and another one located in the lower Narcea (Requejo gauge station) (Figure 2). They have a discontinuous record over the last six decades, but a practically continuous daily record since the 1972-73 hydrological year.

3. Methodology

3.1. *Flow and flood characterization*

In order to understand the geomorphologic evolution of the studied reach of the river and its response to human influence it is, first, necessary to characterize the flow through time and its changes. It was also important to have an idea of the flood behaviour of the river during this time. Fortunately, there is some information about historical floods.

Flow gauge records were analyzed and missing data were completed based on linear correlation between the two gauge stations (Requejo and Corias). There are no records in Requejo prior 1972. Therefore, there is no way for comparing flood record before and after dam closure. To overcome this obstacle, records from Requejo were compared with those from Corias. The comparison allows identifying trends which could be different between both stations and that could be showing the effects of dam on the flow. Fortunately, there is also information about the water inputs to the dam and about water releases from the reservoir, which were analyzed in order to search for potential differences. Also, a frequency analysis based on the data from both gauge stations was done in order to construct the flow frequency curve for each station.

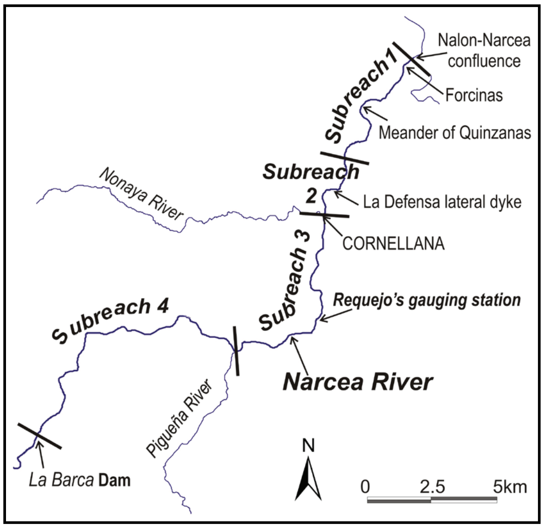

Figure 2. Major drainage network at the study site with indication of main settlements, embankments and location of the four subreaches described in the text.
Figura 2. Principales cauces de la red de drenaje en el área de estudio junto con la localización de las principales actuaciones humanas y la extensión de los cuatro subtramos descritos en el texto.

3.2. *Aerial imagery and post-processing*

Aerial photographs of different years were compiled (Table 1), covering the lower 20 km of the River Narcea: flights from 1957 (source: CECAF; scale: 1:33000), 1985 (CECAF; scale: 1:30000), 1994 (PRINCAST; scale: 1: 18 000) and the orthophotographs of 2007 (PNOA-Spanish National Aerial Orthophotography Plan- with pixel resolution of 0.25x0.25 m).

The collection of aerial photographs was georreferenced using the assistance of ESRI® ArcMap software. The georreferencing process consisted in the identification of several ground control points; this means identifying points which were common and had not changed between the different photographs and the aerial ortophotograph from year 2007 (which was used as base or reference).

Once a complete collection of control points was recognized, the adjustment between the different photographs was done automatically using the "spline" algorithm of ArcMap 9.3. The algorithm adjusts the photography matching the control points between each photograph and the ortophotograph. The error is 0 in the control points and grows with distance from them. The area of the photographs corresponding to the channel, floodplain and surroundings was the focus of the present work. For that reason, control points were selected well distributed across the floodplain and channel, trying to get the best fit in this area of the photographs. Resolution after the rubber sheeting process was 3x3 m for 1957 and 1985 photographs, and 2x2 m for the 1994 (Table 1). To estimate the errors associated with the rubber sheeting process, a collection of 20 independent check points was used, giving an error of ±10 meters for the 1957 photography, ± 6 m for 1985 and ± 8 m for the 1994 (i.e. the ortophotograph from 2007 was used as the base for the georeferencing process).

Next step consisted in mapping the surface covered by active fluvial bars and by the active channel over the georreferenced photographs. Active channel was defined as the surface occupied by the watercourse. It was mapped as the polygon limited by the contact between the water and the trees from the banks or floodplain. Active channel width itself was defined by the ratio between the active channel polygon area and the length of the channel axis (Ham and Church, 2000). Active bars were mapped at a scale varying principally from 1:1000 to 1:1500, and polygon

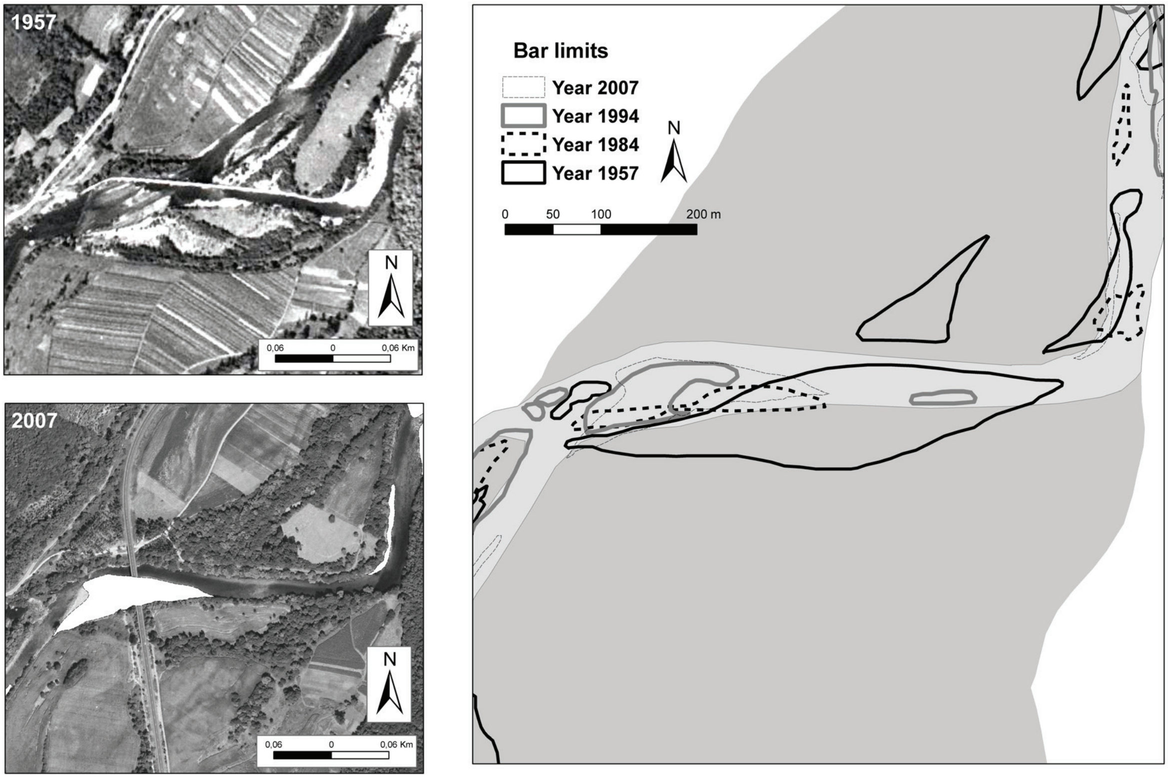

Figure 3. Changes experienced by the channel around the embankment of La Defensa. In the right figure the limits of the fluvial bars in the different aerial photographs are shown. Floodplain surface and channel in 2007 are drawn in dark grey and in pale grey, respectively.

Figura 3. Cambios experimentados por el canal en el entorno del dique de La Defensa. En la figura de la derecha se muestran los límites de las barras fluviales en las diferentes fechas. En gris oscuro se ha dibujado la superficie de la llanura aluvial y en gris pálido el canal en el año 2007.

perimeters were drawn following the contact between the nude bar and the riparian trees cover or the water surface, in each case. Figure 3 shows an example of the bar mapping done for this study.

3.3. *Uncertainties, errors and corrections*

In order to estimate volumetric changes using surface changes mapped over aerial photographs, some corrections and assumptions are needed. First of all, between two photographs of different dates, differences in surface occupied by fluvial bars and the active channel are partly influenced by the discharge and stream characteristics at the moment when the photograph was taken (Ham and Church, 2000). River stage is partly determined by flow discharge. If the discharge is higher in one photo than another, differences in surface values due to stage differences could be wrongly interpreted as a result of erosion processes and/or loose of active sediment; and the opposite, if discharge was lower differences could be mistakenly interpreted as a result of deposition and/or a growing in active sediment storage. So, differences in stage between two photographs may result in an under or overestimation of net-storage changes of mobile sediment. Considering the water stage at snapshot time, the estimated storage of active deposits requires a correction. Correcting the stage effect in active channel width is made through the next expression:

$$\Delta w= a(Q2b-Q1b) \tag{1}$$

where *w* is the active channel width, *Q* the discharge at the moment when the photograph was taken (Ham and Church, 2000), and *Δw* is positive for higher flows in the later date and the inverse for lower flows.

Once the active channel is mapped, active channel width values are plotted against discharge at the day when the photograph was taken. Discharge values were obtained from the Requejo gauging station. Resulting plotted data are adjusted through a potential equation, with the form of equation 1 (Figure 4). The adjusting equation is then used to do the correction on active channel width values (Ham and Church, 2000). After this process, the correction of surface values was done. The correction of surface values allows comparing maps generated for different years.

For that, the next expression was applied:

$$\Delta S= \Delta w \; x \; L \tag{2}$$

where *ΔS* is the surface correction and L the reach length (Ham and Church, 2000). To estimate sediment volumes it is also necessary to make an assumption for the value of the active bed layer thickness; here, we used the mean of height differences between the top of the bars and the bottom of the channel (Ham, 1996; Ham and Church, 2000). To do this calculation, a collection of profiles available for the study site was used. These profiles were obtained from the LINDE project (CHN, 2002). So, volume changes through time are understood here as the product of areal changes and the assumed mobile bed depth. Bar correction factor for the volumes is estimated through the next expression:

$$\Delta V_c= \Delta S \; x \; d \tag{3}$$

where *d* is the bed material thickness. The net storage change is then estimated as:

$$\Delta V= (V_d - V_e + \Delta V_c) \tag{4}$$

Table 1. Aerial photographs used for the present research and information about scale, resolution an error after georreferencing process.
Tabla 1. Fotografías aéreas usadas para el presente trabajo con información concerniente a la escala, resolución y error tras el proceso de georeferenciación.

Year	Date	Scale	Resolution (after georeferencing)	Error (m)
1957	22-5-57	1:30 000	3x3 m	+/- 10
1985	17-4-85	1:30 000	3x3 m	+/- 6
1994	6-10-94	1:18 000	2x2 m	+/- 8
2007	10-9-07	…*	0.25x0.25 m	…

* Ortophotograph from 2007 has not scale, because it was acquired in digital support and georreferenced.

where V_d is bar deposition volume and V_e bar erosion volume. If the discharge was higher in the snapshot time, ΔV_c should be positive, because bar surface extension would be underestimated in that photography. In contrast, at lower flows, ΔV_c should be negative, because water surface extension is underestimated and bar surfaces overtestimated. Finally, it was also needed to assume a value for the bed material porosity. For this we used 0.25 (volumes of empty spaces/total volume of sediment), the value proposed by Martin and Church (1995) for gravel and cobble beds.

It should be remembered that after these corrections, the uncertainty linked to errors in the aerial imagery post processing is still present. Errors related with the georreferencing process were described in the previous subsection (Table 1). Cartography precision would be biased by the image with poor resolution after rubber sheeting; that is, 10 meters (photograph from 1957). Squaring this value and multiplying it by the standard deviation of the depth, give us an error of ± 200 m^3 in the estimations of volumes of sediment.

3.4. *Reach division*

In order to a better interpretation of the results, the study reach was divided in different subreaches (Figure 2). Four different subreaches were defined in the lower Narcea, numbered from downstream to upstream. *Subreach 4* was defined starting at the dam and ending at the confluence between Pigüeña and Narcea rivers. *Subreach 4* is characterized by a narrow and incised channel. In its upper third, the river channel is incised on quartzite bedrock, with geomorphic features typical of a bedrock river channel (Tinkler and Wohl, 1998; Ortega Becerril, 2010). *Subreach 3* is located between the confluence Narcea-Pigüeña and the junction of Nonaya and Narcea rivers. Unlike *Subreach 4*, there is a clear predominance of floodplain development. Over the aerial photograph from 1957, *Subreach 3* shows a marked braided nature. In these two *subreaches* (*3* and *4*) there are no protection works (bank dykes or similar).

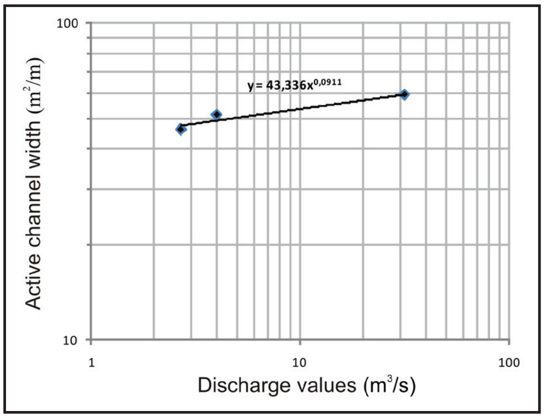

Figure 4. Active channel width plotted against discharge at the moment that each aerial photograph was taken. Adjustment equation is used for the correction due to river stage on each photograph. Year 1957 was not used in the regression because there were no data of available from the Requejo gauging station.
Figura 4. Anchura activa de canal, proyectada frente al valor de descarga en el día en que fue tomada cada fotografía aérea. La ecuación de ajuste obtenida es utilizada para realizar la corrección en cada fotografía debida al nivel del agua. El año 1957 no fue usado para la regresión porque no había datos disponibles para la estación de Requejo para esa fecha.

To define *subreaches 1* and *2* we used a historical morphometric criterion: over the aerial photograph of 1957, an upstream braided subreach and a downstream meandering one were distinguishable in the lower 10 km of the River Narcea (Fernández *et al*., 2006). The former was classified as *Subreach 2* and the later, as *Subreach 1*. *Subreach 1* is channelized in roughly 40% of its length, while about 30% of length of *Subreach 2* has embankment works; but *Subreach 2* has been channelized for a longer period of time (i.e. since 1955).

4. Results

4.1. *Flood frequency and magnitude*

As it was stated above, there are no gauge records for the Requejo gauging station before 1972. So, a comparison between the records from Requejo (gauging station downstream from the dam) and Corias (upstream from the dam) since 1972 was done, with the purpose of identifying trends which could indicate the hydrological effects of the dam on flow, hence energy, inputs to the fluvial system. Figure 5 shows the evolution of maximum annual discharges through time. The same trend upstream and downstream the dam can be observed, owing to the small impoundment capacity (i.e. flood regulation) exerted by the reservoir on river flows. Figure 6 represents the mean monthly water inputs to the dam and releases from it. Monthly inputs and releases have essentially the same value.

The ratio between the capacity of the dam (34 hm^3) and mean annual water yield from the upstream drainage basin (904 hm^3) was calculated in order to evaluate the regulation capacity of the dam, from the impoundment ratio suggested by Batalla *et al*. (2004). The value was 0,038 (i.e. 3.8%).

Flood recurrence curves show the same behaviour upstream and downstream from the dam (Figure 7). The form of the curve is the same for the two locations. Values for Requejo are obviously higher, because of its larger drainage area.

Historical information and geomorphological studies on floods during the last six decades shows seven major events. Ordered from larger to smaller of floodplain inundated area, events are: 1959 >1983 > (1961-1966) > 1998 > 2010 > 1993, ranked through the method proposed by Fernández *et al*. (submitted for publication). Summarizing, there were three major flood events before dam construction and four major flood events after construction. Also, since 1972, around 30 flood episodes of low magnitude (but still higher than bankfull discharge) has been observed in the gauging records.

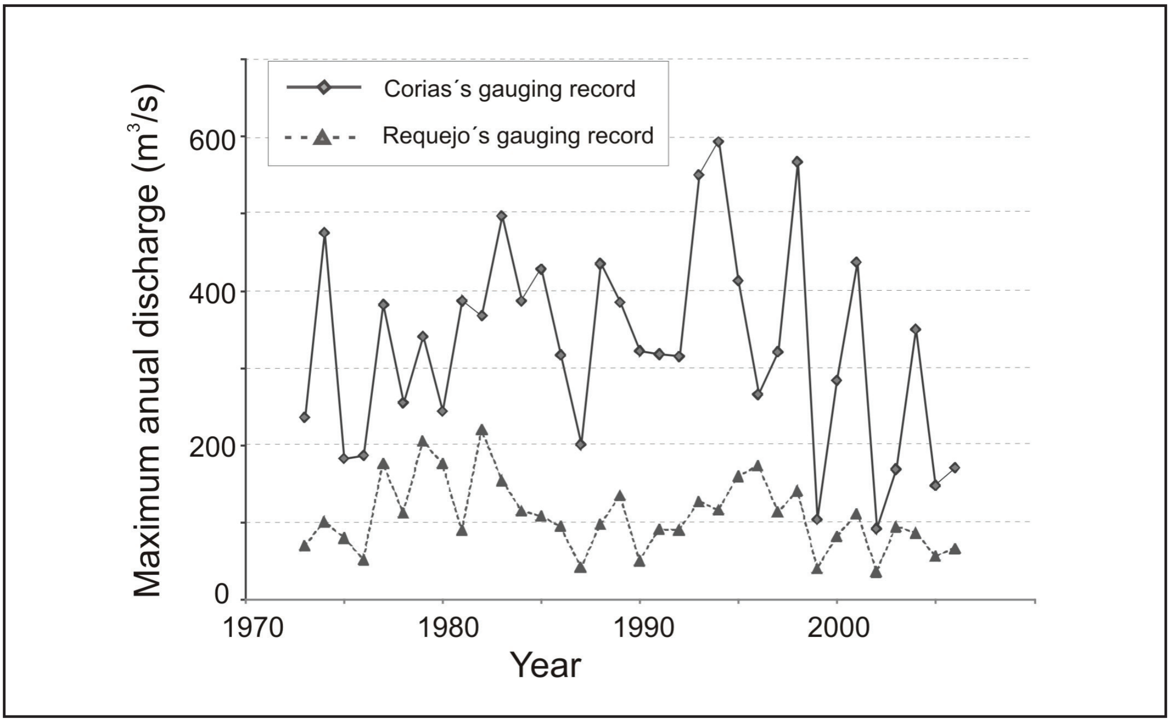

Figure 5. Maximum annual discharges since 1970 plotted using gauging data from Requejo and Corias gauging stations. Succession of peaks and valleys show a similar pattern.
Figura 5. Máximos valores anuales de descarga desde 1970 proyectados usando datos de las estaciones de aforo de Requejo y Corias. La sucesión de picos y valles en el gráfico muestra un patrón similar.

Table 2. Active channel width values for each year.
Tabla 2. Anchura activa de canal para cada año.

	Aerial photography year			
	1957	1985	1994	2007
Subreach 1	56 m	40 m	52 m	51 m
Subreach 2	82 m	71 m	56 m	64 m
Subreach 3	65 m	57 m	57 m	53 m
Subreach 4	44 m	35 m	37 m	33 m
Total reach	57 m	46 m	48 m	46 m

4.2. *Changes in active channel width and volumes of active sediment*

4.2.1. Reach scale changes

At the whole reach scale, an important reduction in active channel width (Table 2) from 1957 to 1984 (from 56 m to 46 m) can be observed. Since then, it remains practically without changes. Results of changes in volumes of sediment are presented in Table 3 and Figure 8. For the whole study reach, a reduction in the volumes of active sediment through the whole period analyzed (1957-2007) can be found: overall, active sediment volume has been reduced by 1800000 m^3 (36000 m^3/year). The same behaviour can be observed when considering each interval of time between temporal consecutive photographs (1957-85; 1985-1994 and 1994-2007).

4.2.2. Subreach scale changes

At the subreach scale, several changes shall be emphasized (Tables 2 and 3; Figure 9):

- *Subreach 3* and *Subreach 4* show a comparable behaviour through time. During the period 1957-1985 (dam closure in 1966) riverchannel experienced a decrease in active channel width. From 1985 to 2007, both reaches had not experienced important changes in active channel width, which remained more or less constant.

- Remarkable changes in active channel width have been found in *Subreach 2*, where channel reduced 18 m during the whole study period. There, channel width reduced considerably (82 m to 56 m, i.e. -32%) for the period 1957-1994; while from 1994 to 2007, channel width increased from 56 m to 64 m.

- From 1957 to 1985, channel width in the *Subreach 1* reduced from 56 m to 40 m. From 1985 to 1994, it increased again to 52 m. Since then, active channel width remained stable until 2007 (last year analyzed).

When considering changes in volumes of sediment, both *subreaches 1* and *2* show a similar evolution pattern, with reduction in the volume of active sediment stored in bars from 1957 to 1985 (65000 m^3 in *Subreach 1* and 28000 m^3 in *Subreach 2*) and also from 1985 to 1994 (270000 m^3 in *Subreach 1* and 230000 m^3 in *Subreach 2*). In contrast, from 1994 to 2007 an increasing in the deposits of transportable sediment was observed (130000 m^3 in *Subreach 1* and 50000 m^3 in *Subreach 2*).

In *Subreach 3* there is a strong reduction in the volume of sediment stored in active bars for the whole period (1200000 m^3). In *Subreach 4* it was also found a decreasing in the volume of active sediment from 1957 to 1985 (190000 m^3). When looking at the bar

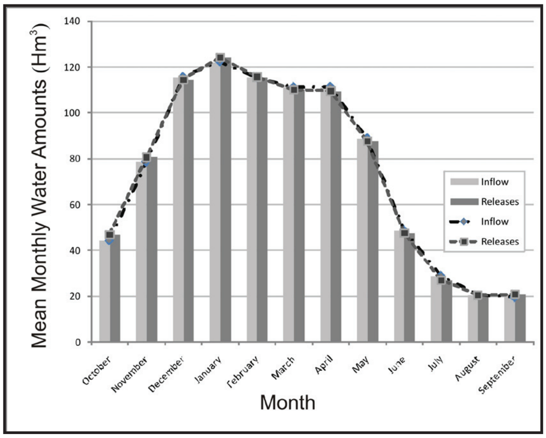

Figure 6. Mean monthly water inflow and releases to La Barca Dam.
Figura 6. Entradas y salidas mensuales medias de agua en la presa de La Barca.

mapping, it is in the lower two thirds of *Subreach 4* where this growing can be observed, due to its intrinsic alluvial nature. From 1985 to 2007, there is a reduction in the volume of active deposits for the whole *Subreach 4* (440000 m^3). Loses of active sediment for these two *subreaches* are between *3* and *5* times the values described for the other two subreaches (Figure 9).

4.3. *Long-term trends*

In Figure 9, we plotted the cumulative changes in the volumes of active sediment through time. Changes from the whole reach are important from 1957-1985 and reduction became stronger in the second period (1985-1994). This reduction is related to the general lose of mobility of sediment in the four subreaches. For the whole study reach, the increment of active areas increased drastically for the period 1994-2007, despite some reduction still persisted in areas of the *subreaches 3* and *4*. The slight positive trend for reaches *1* and *2*, together with the low reduction for *subreaches 3* and *4*, buffer the overall reduction trend observed for the whole studied reach.

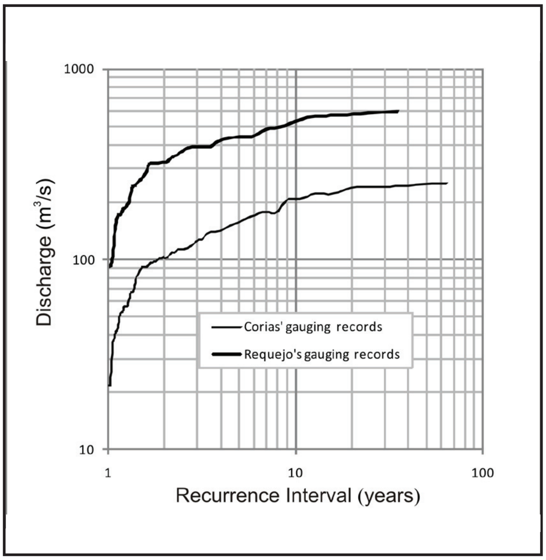

Figure 7. Flow duration curves for the two gauging stations Requejo y Corias.
Figura 7. Curvas de recurrencia para las estaciones de aforo de Requejo y Corias.

5. Discussion

Hydrological records from the two gauging stations located upstream and downstream of the *La Barca* Dam shows a similar behaviour of the maximum annual discharges despite of the presence of the dam (Figure 5). The ratio between dam capacity and water yields from upstream basin (Batalla *et al.*, 2004, Graf, 2006) is very low. The low impoundment ratio means that the reservoir is only able to store a minor fraction of the total inflow of water. So, it is not able either to exert a strong control over downstream flows. Taking a view on the mean monthly inputs and outputs to the dam indicate that operators rules agree with that. The water amounts releases from the dam are essentially the same as the water inflows to the reservoir (Figure 7). Furthermore, Marcuello and Incio (2009) carried out a numerical model of the dam and concluded that *La Barca* Dam has not effect on routing peak flows. In addition, as it was shown before, overbankfull floods are very frequent and dam seems to have no influence on the persistence of major events. Moreover, Fernández *et al*. (in press) have found no influence of dams over flood frequency in the whole Nalon-Narcea basin.

In summary, it is evident that the *La Barca* Dam exerts little hydrological control downstream, so it does not influence floods ability to carry out geomorphologic work in the river. In consequence, it does not influence the energy inputs to the system, but it still could exert geomorphologic influence downstream acting as a sediment trap. Despite the flow and flood analysis does not show any major trend or influence of the dam on the hydrology over the period 1957-2007, this study shows that there is a clear trend to a reduction in mobility of fluvial deposits over this 50 year record (see results section). As a consequence, an alternative explanation different to the hydrological effects of the dam should be pursued. The *La Barca* Dam captures the upstream coarse sediment supply. As a result, the balance between the transport capacity of the stream and the supply of sediment was broken. The excess of transport energy probably have entailed channel incision. This effect of dams has been described before by other authors such as “hungry water” effect (e.g. Kondolf, 1997; Vericat *et al*., 2008).

Embankment works affected only the *subreaches 1* and *2*. These subreaches concentrate the larger bank erosion in the river. The effects of embankment works were superimposed to the effects of the dam and this join action may explain the important development of bank erosion in both subreaches. As it was presented in the results section, for the time period 1957-1994 both subreaches showed an important reduction in the storage of active deposits; and even active channel width decreased strongly. Probably, that reduction is strongly related with the first two embankment works built along the River Narcea:

- La Defensa lateral dyke, finished in 1955 (Figure 3). This channelization caused a sudden decrease in active channel width (narrowing) that led to abandoning of a secondary channel. This fact produced a change in the river path from a braided system to a nearly “meandering” pattern. Ten years after dyke was built up, the channel started experiencing incision. This incision can be noted nowadays in the field, especially in the right bank located both 1 km upstream from the dyke and 3 km downstream (Fernández *et al*., 2006).

- The first channelization at Quinzanas, an embankment placed on the left margin, which slightly changed river path and caused the abandonment of the left bank, also inactivating a secondary channel.

From 1994 to 2007 an increase in the volumes of active sediment for both subreaches is observed. This increase was interpreted by Fernandez *et al*. (2006) at the light of the evolution channel model (Schum *et al*., 1984; Simon, 1989). They argued that last embankment interventions had supposed a channel section widening, which has made possible aggradation due to the rise in channel section. Results presented here agreed with this interpretation. In *Subreach 2*, the embankment of Cornellana was finished in 1994, which supposed a channel widening (seen the increase in active width for the last time period). As a consequence, a large lateral bar was developed on the right bank. In *Subreach 1*, the meander at Quinzanas underwent a second embankment in 1992. As a result, new lateral bars have grown along the channel bed (Fernández *et al*., 2006). An important source of sediment supply for this growing process may be the sediment provided locally by bank erosion at some points along the reach.

As it was indicated before, the temporal evolution was slightly different for *subreaches 3* and *4*. They experienced a continuous reduction in the storage of active deposits during the analyzed period. According to our results, this behaviour can be related with the dam construction and the related channel erosion

Table 3. Changes in volumes of sediment stored in exposed gravels in the different subreaches of the River Narcea.
Tabla 3. Cambios en los volúmenes de sedimento almacenado como gravas expuestas en los diferentes subtramos diferenciados en el río Narcea.

	1957-1985		1985-1994		1994-2007		1957-2007	
	m^3	m^3/yr	m^3	m^3/yr	m^3	m^3/yr	m^3	m^3/yr
Subreach1	-65000	-2300	-270000	-30000	130000	10000	-205000	4100
Subreach 2	-28000	-1000	-230000	-26000	50000	3900	-208000	200
Subreach 3	-700000	-25000	-350000	-40000	-150000	-12000	-1200000	24000
Subreach 4	-190000	-6700	-360000	-40000	-80000	-6200	-630000	-12600
Total reach	-550000	-20000	-1200000	-130000	-65000	-5000	-1800000	-36000

effect. Degradation trends after dam construction are non-linear with time (Simon *et al*., 2002): first effects after dam closure tend to occur in depth, causing channel incision (Wellmeyer *et al*., 2005; Vericat and Batalla, 2006; Vericat *et al*., 2008) and sometimes, channel widening and bank erosion (Anders-Brandt, 2000); and later, armouring, downstream fining and colonization of active areas by vegetation (Vericat and Batalla, 2004; Batalla *et al*., 2006). The effect of sediment starved water should be more evident over alluvial reaches that in rocky ones.

After dam closure, starved water started the erosion processes. During the period 1957 to 2007, the lower Narcea recorded three large floods (i.e. 1959, 1983 and 1998). The first two events occurred during the first study period (1957-1985) and these events probably caused the incorporation of sediment from the margins to the active surface in the lower *Subreach 4*. This partly explains why the reduction in active sediment was not as strong as it was in the next subreach. In *Subreach 3*, due to its more braided nature, the lack of coarse sediment supply involved the abandonment of secondary channels and the reduction of activity in marginal sediment deposits. This explains the strong reduction in volumes of active sediment found here for the first time period after dam closure. After this "reaction period", since 1985 the abandonment processes prevailed in *Subreach 4*, characterized by a slightly sinuous path. This process probably explains most of the lose in coarse active sediment for *Subreach 3* and also for *Subreach 4* (in addition to the absence of any important tributary, within and immediately upstream the subreach; hence, no local supply takes place), and its colonization by riparian vegetation.

Fernández-Iglesias and Fernández García (2008) analyzed the evolution of several Cantabrian rivers (including the Narcea) during the last six decades. In that work they described a slow trend to channel incision. They related this trend mainly with changes in land uses. They observed the clear trend to incision in the River Narcea, which was the only one of the six rivers which was affected by dam construction. Therefore, based in this observations and in another studies carried out before (e.g. Fernández *et al*., 2006; CHC, 2009), together with the results presented here, it could be concluded that the human interventions (dam and embankments) may explain most of the changes in volumes of active sediment observed from our sequential study of aerial photographs.

In general, for the whole study river reach and the whole period analyzed, reduction in the volumes of transportable sediment stored in fluvial bars was described. The initial reduction and later stabilization of active channel width implies that this reduction is not principally the consequence of bank erosion or erosive processes on lateral bars, except locally at certain points. This phenomenon should be interpreted instead, as a consequence of a continuous process of abandonment of lateral bars and their progressive incorporation to the floodplains (due to human alterations) and occupation by riparian forests, with the consequent reduction in exposed gravels.

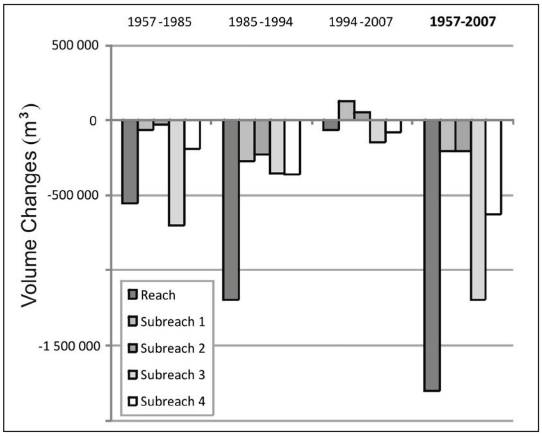

Figure 8. Volume changes in the storage of active sediment through time, along the whole studied reach (first bar of each group in the histogram) and the different subreaches.

Figura 8. Cambios en los volúmenes de almacenes de sedimento activo a lo largo del tiempo, para todo el área de estudio (primera barra en cada histograma) y para cada subtramo.

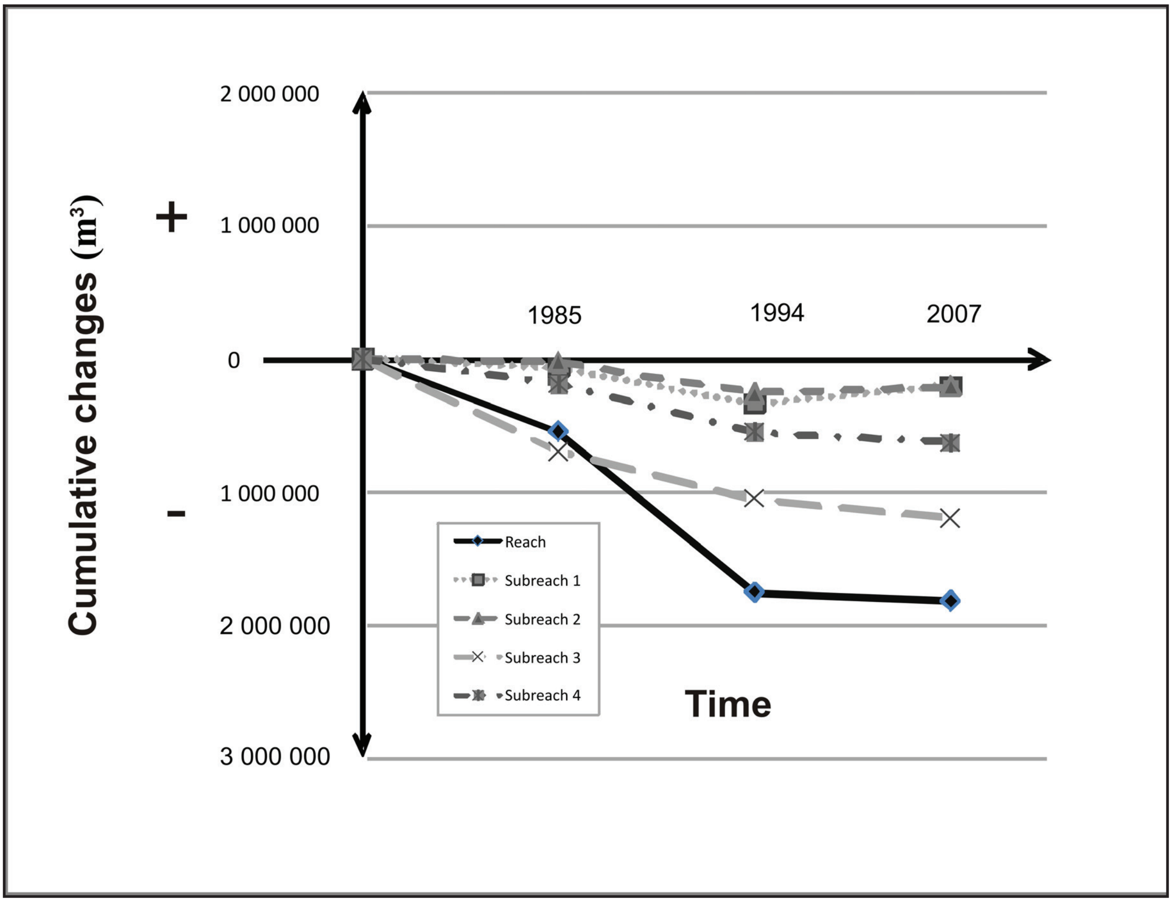

Figure 9. Cumulative changes through time in volumes of mobile sediment stored in the lower River Narcea.
Figura 9. Cambios acumulados a lo largo del tiempo en los volúmenes de sedimento móvil almacenados en el bajo Narcea.

6. Conclusions

The present work presents an attempt to estimate volumetric changes through time in mobile sediments in the lower River Narcea, from changes in active bar surface identified on aerial photographs taken at several years. Thus, volume changes have been estimated as the product of surface changes and active sediment depth. Furthermore, a correction was done on the surface values obtained in the mapping process, in order to overcome the effect of flow discharge and stage level on the photo interpretation around the river channel.

Results obtained show a general trend of lost of active deposits in the lower Narcea during the last six decades. This trend reflects a progressive abandonment of lateral deposits and its colonization by riparian forests. This process is most probable as the consequence of the human intervention in the channel, particularly the dam closure in 1966 and the several embankment works carried out in the lower 10 km of river during the last half of century; together with land use changes (Fernández Iglesias and Fernández García, 2008). Active channel width suffered a strong reduction from 1957-1985 for the whole study reaches. After that, it remained roughly constant, reflecting the stabilization by vegetation. After dam closure, all subreaches showed a reduction in the volumes of active sediment. This reduction was stronger for the subreaches closer to dam (*Subreaches 3* and

4), and continued during the last period analyzed. *Subreaches 1* and *2* showed an increase for the last time period analyzed, related with embankment works.

Research shall be continued by incorporating data on the volumes of sediment lost in the river banks by erosion processes during the last six decades. It would allow an attempt to assessing the local supply of sediment in the lower reach of river and would also allow a better quantification of active sediment transfers during this time.

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References

Anders-Brandt, S. (2000). Classification of geomorphological effects downstream of dams. *Catena*, 40, 375-401.

Ashmore, P.E.; Church, M.A. (1998). Sediment transport and River morphology: a paradigm for study. In: *Gravel-bed Rivers in the Environment. Proceedings of the Fourth International Workshop on Gravel Bed Rivers* (P.C. Klingermann; R.L. Beschta; P.D. Komar; J.B. Bradley, eds.). Water Resources Publications. Littleton, Colorado, 115-148.

Batalla, R.J.; Gomez, C.M.; Kondolf, G.M. (2004). Reservoir-induced hydrological changes in the Ebro River basin (Northeastern Spain). *Journal of Hydrology*, 290 (1-2), 117-136.

Batalla, R.J.; Vericat, D.; Martínez, T.I. (2006). River-channel changes downstream from dams in the lower Ebro River. *Zeitschrift für Geomorphologie,* Suppl. B., 143, 1-14.

CHN (2002). Proyecto LINDE: *Asistencia técnica para el estudio y delimitación previa del Dominio Público Hidraúlico correspondiente a la 2ª Fase-3ª Etapa del proyecto LINDE (Cuenca Hidrográfica del Norte).* Confederación Hidrográfica del Norte, Ministerio de Medio Ambiente. Inédito.

CHC (2009). *Restauración ambiental del tramo bajo del río Narcea en los términos municipales de Salas* y *Pravia (Asturias)*. Documento abierto para el proceso de participación pública, 12 de Noviembre de 2009. Confederación Hidrográfica del Cantábrico, Ministerio de Medio Ambiente, Rural y Marino.

Emmett, W.W. (1980). *A field calibration of the sediment-trapping characteristics of the Helley-Smith bedload sampler*. USGS Professional Paper 1139, 44 pp.

Farias, P.; Marquínez, J. (1995). El relieve. En: *Geología de Asturias* (C. Aramburu; F. Bastida, eds.). Ediciones Trea. Gijón, 163-182.

Fernández Iglesias, E.; Fernández García, M. (2008). La movilidad de los cauces en los ríos del NO Peninsular. En: *Geomorfología y territorio* (A. Pérez Alberti; J. Bedoya, (eds.). Santiago de Compostela, 211-214.

Fernández, E.; Colubi, A.; González-Rodríguez, G.; Anadón, S. (in press). Integrating statistical information concerning historical floods: ranking and interval return period estimation. *Natural Hazards.*

Fernández, E.; Tirador, P.; Marquínez, J. (2006). Impacto de las canalizaciones en el río Narcea (Asturias). En: *Trabajos de Geomorfología en España 2006-2008* (J. Benavente; F.J. Gracia, eds.), X Reunión Nacional de Geomorfología, S.E.G., Cádiz, 509-520.

Graf, W.L. (2006). Downstream hydrologic and geomorphologic effects of large dams on American rivers. *Geomorphology*, 79, 336-360.

Ham, D. (1996). *Patterns of channel change on Chiliwack River, British Columbia.* M.Sc. Thesis, Department of Geography, University of British Columbia, Vancouver.

Ham, D. (2005). *Morphodynamics and sediment transport in a wandering gravel-bed channel: Fraser River, British Columbia.* PhD. Thesis, Department of Geography, University of British Columbia. Vancouver.

Ham, D.; Church, M. (2000). Bed material transport estimated from channel morphodynamics: Chilliwack river, British Columbia. *Earth Surface Processes and Landforms*, 25, 1123-1142.

Hassan, M.A.; Schick, A.P.; Laronne, J.B. (1984). The recovery of flood-dispersed coarse sediment particles. *Catena Suppl*., 5, 153-162.

Helley, E. J.; Smith, W. (1971). *Development and calibration of a pressure-difference bedload sampler.* U.S. Geol. Survey Open-File report, 18 pp.

Hughes, M.L.; McDowell, P.F.; Andrew Marcus, W. (2006). Accuracy assessment of georectified aerial photographs: Implications for measuring lateral channel movement in a GIS. *Geomorphology*, 74 (1-4), 1-16.

INDUROT (2004). *Creación de un sistema de información de las zonas inundables y de avenidas torrencial del Principado de Asturias.* Consejería de Justicia, Seguridad Pública y Relaciones Exteriores (112 Asturias), Principado de Asturias. Inédito.

Kondolf, G. M. (1997). Hungry Water: Effects of dams and gravel mining on river channels. *Environmental Management*, 21 (4), 551-553.

Kuhlne, R. A.; Bingner, R. L.; Foster, G. R.; Grissinger, E. H. (1996). Effects of land use changes on sediment transport in Goodwin Creek. *Water Resources Research*, 32 (10), 3189-3196.

Lane, S.N.; Richards, K.S. (1997). Linking forms and processes. *Earth Surface Processes and Landforms*, 22, 249-260.

Lewin, J.; Hughes, D. (1976). Assessing channel change on Welsh rivers. *Cambria*, 3, 1-10.

Marcuello, C.; Incio, L. (2009). Estudios hidrológicos e hidráulicos en el marco del Sistema Nacional de Cartografía de Zonas Inundables. *Jornadas de Ingeniería del Agua, Agua y Energía*. Madrid, 69-70.

Martin, Y.; Church, M. (1995). Bed material transport estimated from channel surveys: Vedder river, British Columbia. *Earth Surface Processes and Landforms*, 20, 347-361.

Milhous, R.T. (2005). *Climate change and changes in sediment transport capacity in the Colorado Plateau, USA. In: Sediment Budgets 2: Proceedings of symposium S1 held durning the Seventh IAHS Scientific Assembly at Foz do Iauacu, Brazil, April 2005* (A.J. Horowitz; D.E. Walling, eds.). IAHS Press Publication 292. Oxfordshire, 271-278.

O'Connor, J.E.; Jones, M.A.; Haluska, T.L. (2003). Flood plain and channel dynamics of the Quinault and Queets Rivers, Washington, USA. *Geomorphology*, 51, 31-59.

Ortega Becerril, J.A. (2010). Tipos de ríos en roca. Clasificaciones. En: *Patrimonio geológico: Los ríos en roca de la Península Ibérica* (J.A. Ortega; J.J. Durá, eds.). Instituto Geológico y Minero de España, Serie Geología y Geofísica, 4, Madrid, 37-54.

Reid, I.; Frostick, L. E.; Layman, J. T. (1980). The continuous measurement of bedload discharge. *Journal of Hydraulic Research*, 18, 243-249.

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

Schum, S.A.; Harvey, M.D.; Watson, C.C. (1984). Incised Channels: Morphology, Dynamics and Control. Water Resources Publication, Littleton, Colorado.

Simon, A. (1989). A model of channel response in disturbed alluvial channels. *Earth Surface Processes and Landforms*, 14, 11-26.

Simon, A.; Thomas, R.E.; Curini, A.; Douglas Shields Jr. F. (2002). Case study: Channel stability of the Missouri river, Eastern Montana. *Journal of Hydraulic Engineering*, 128 (10), 880-890.

Surian, N. (1999). Channel changes due to river regulation. *Earth Surface Processes and Landforms*, 24, 1135-1151.

Tinkler, K.; Wohl, E. (1998). A primer on Bedrock Channels. In: *Rivers over Rock: Fluvial Processes in Bedrock Channels* (K.J. Tinkler; E. Wohl, eds.), American Geophysical Union, Geophysical monograph series, 107, Washington, 1-18.

Vericat, D.; Batalla, R.J. (2004). Balance de sedimentos en el tramo bajo del Ebro. *Cuaternario y Geomorfología*, 20 (1-2), 79-90.

Vericat, D.; Batalla, R.J. (2006). Sediment transport in a large impounded river: The lower Ebro, NE Iberian Peninsula. *Geomorphology*, 79, 72-92.

Vericat, D.; Batalla, R.J.; García, C. (2006). Breakup and reestablishment of the armour layer in a large gravel-bed river below dams: the lower Ebro. *Geomorphology*, 76, 122-136.

Vericat, D.; Batalla, R.J.; García, C. (2008). Bed-material mobility in a large river below dams. *Geodinamica Acta*, 21, 3-10.

Walling, D.E. (2009). *The Impact of Global Change on Erosion and Sediment Transport by Rivers: Current Progress and Future Challenges*. The United Nations World Water Assessment Programme Scientific Side Paper Series. UNESCO, Paris, 30 pp.

Wellmeyer, J.L.; Slattery, M.C.; Phillips, J.D. (2005). Quantifying downstream impacts of impoundment on flow regime and channel planform, lower Trinity River, Texas. *Geomorphology*, 69, 1-13.

Werritty, A. (1997). Short-term changes in channel stability. In: *Applied Fluvial Geomorphology for River Engineering and Management* (C.R. Thorne, C.R.; R.D. Hey; M.D. Newson, eds.). John Wiley & Sons Ltd, New York, 47-65.