Universitat de Lleida

Analysis of hydro-sedimentary processes and impacts affecting river basins and channels

Gemma Piqué Altés

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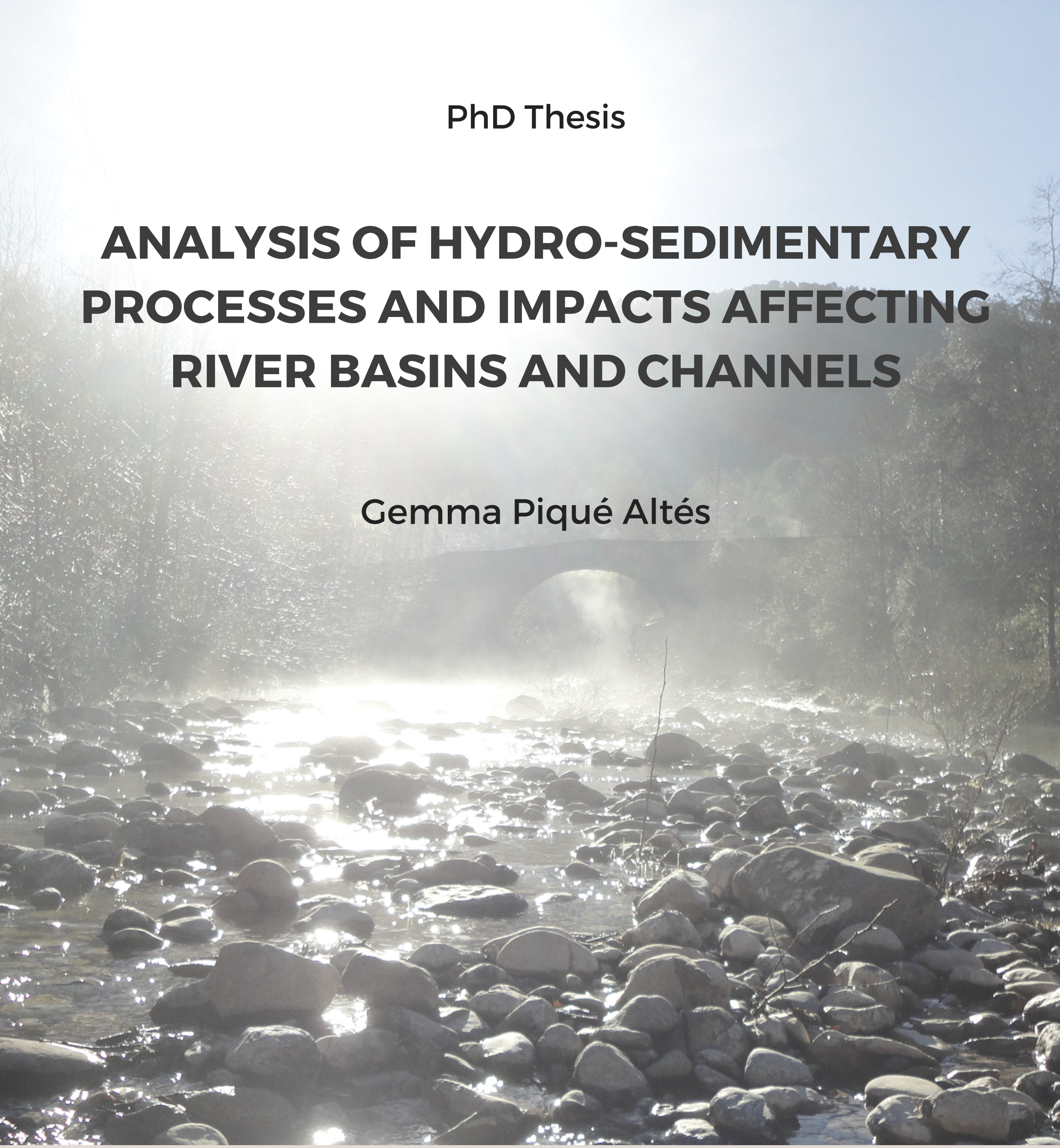
PhD Thesis

ANALYSIS OF HYDRO-SEDIMENTARY PROCESSES AND IMPACTS AFFECTING RIVER BASINS AND CHANNELS

Gemma Piqué Altés



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Cover photo: River Muga in Sant Llorenç de la Muga, December 2014 (Author: J.P. Casas-Ruiz)

Universitat de Lleida

TESI DOCTORAL

ANALYSIS OF HYDRO-SEDIMENTARY PROCESSES AND IMPACTS AFFECTING RIVER BASINS AND CHANNELS

Gemma Piqué Altés

Memòria presentada per optar al grau de Doctor per la Universitat de Lleida
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Directors

Dr. Ramon J. Batalla
Dr. Sergi Sabater

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Note

This file contains scientific articles that have been slightly modified in order to correct spelling or other small errors, as well as to homogenise the style of the text. However, contents and results of the work have not changed.

“However far the stream flows, it never forgets its source.”

(*Nigerian proverb*)

AGRAÏMENTS

Sembla que això s'acaba, i no voldria posar el punt i final sense donar les gràcies a totes aquelles persones que directa o indirectament han posat el seu granet de sorra (o més d'un) en aquesta tesi. Ara entenc la por que sempre es comenta en aquest apartat, i és que espero no deixar-me ningú.

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* Que la paraula 'gràcies' aparegui 19 vegades i que la paraula 'agrair' surti 7 vegades en tan sols 3 pàgines no és pas casualitat...

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SUMMARY
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SUMMARY

Mediterranean rivers are characterised by naturally high **sediment loads**, mainly as a consequence of hydric erosion but also owing to the intensity of hydro-climatological episodes (i.e. floods). Flow regimes also display a remarkably large variability in this region. **Anthropic** pressures on river basins are also high due to elevated and increasing water demands, which are typically out-of-phase in relation to temporal availability of water resources. Owing to this complex hydroclimatic and socioeconomic setting and, in order to ensure water supply, a widespread construction of large **dams**, mostly during the second half of the 20th century, has taken place. In addition, observable changes in land use, mostly afforestation in catchment headwaters, have reduced runoff from river basins, thus water production and yield, threatening water supply to lowlands, where main economic activities are mostly located. Dams modify **water and sediment fluxes** of rivers, entirely affecting the functioning of fluvial ecosystems. This thesis examines water and sediment budgets and related fluvial processes, both in natural rivers and in relation to anthropic impacts, in selected Mediterranean river basins. Research was conducted in catchments located in the north-western part of the Mediterranean basin, which were specifically selected to accomplish the objectives of the research. For this purpose, a **multitemporal** and **multispatial** scale research design was followed i.e. from experiments in laboratory artificial streams to field measurements and experiments in representative river reaches, and database analysis of large river basins. Overall, results illustrate the degree of **alteration** of rivers hydro-sedimentary dynamics, mostly in relation to dam presence; but also on how basin hydro-sedimentary dynamics may affect reservoirs water storage capacity, thus their long-term viability. Headwater catchments affected by intense hydrosedimentary processes release and transport large sediment loads, a fact that severely affects the capacity of downstream reservoirs. In-channel **sediment storage** modulates rivers sediment budgets and the temporal supply of sediment (i.e. River Isábena). In contrast, the siltation threat in reservoirs located in basins with low geomorphic activity is much lower (i.e. River Muga). The research also shows how rivers **hydrology** is altered below dams, from daily to the annual scale, with most intense effects observed on flood magnitude and frequency; whereas dams trap sediment and break the continuity of sediment transport, hydrological alterations directly affect the whole rivers sedimentary regime. Below dams, stabilisation of river bed is observed, a fact that is evidenced by armouring and **biofilm** colonisation; these two counter-effecting processes gradually increase the required competence of flow discharges to entrain sediments and reactive fluvial dynamism. The thesis illustrates water and sediment dynamics in Mediterranean rivers, supplies new evidences on the degree of impact of human activities on river processes and some of their key bio-physical interactions, and overall emphasises the need for a continued sound **water and sediment management** of these fragile ecosystems and landscapes, to achieve an optimal and balanced use of water resources and the preservation of stream ecosystems.

Keywords: river hydrology, sediment transport, sediment budget, dams, sediments-biofilm interaction, measurements, experimentation, Mediterranean basins.

RESUM

Els rius mediterranis es caracteritzen per transportar elevades càrregues de **sediments** de forma natural, sobretot com a conseqüència d'erosió hídrica, però també degut a l'elevada intensitat dels episodis hidro-climàtics (crescudes). Els rius d'aquesta regió presenten una alta variabilitat pel que fa al seu règim de cabals i, a més, estan sotmeses a elevades **pressions antròpiques** i a una demanda creixent d'aigua, que no coincideix amb la disponibilitat temporal dels recursos hídrics. A causa d'aquest complex entorn hidro-climàtic i socio-econòmic, i amb la necessitat d'assegurar el subministrament d'aigua, durant la 2a meitat del segle XX es van construir **embassaments** de forma generalitzada. A més, els canvis en els usos del sòl, principalment reforestació a les capçaleres dels rius, han provocat una reducció de l'escolament i la generació d'aigua en rius. Aquest fet amenaça el subministrament d'aigua a les parts baixes de la conca, on majoritàriament tenen lloc les activitats econòmiques. Les preses modifiquen els **fluxos d'aigua i sediments** dels rius, afectant també el funcionament dels ecosistemes fluvials. Aquesta tesi estudia balanços d'aigua i sediments en conques mediterrànies, així com també processos fluvials relacionats, tant en rius naturals com en rius afectats per impactes antròpics. La recerca va dur-se a terme en conques situades al nord-oest del mar Mediterrani, i van ser escollides en funció de les seves característiques per a respondre als objectius plantejats. Per aquest motiu, es va realitzar un estudi a escala **multi-temporal** i **multi-espacial**, que va incloure experiments en canals de laboratori, mesures de camp i experiments en trams de rius representatius, així com també l'anàlisi de bases de dades a nivell de conca. En general, els resultats mostren l'**alteració** de la dinàmica hidro-sedimentària del riu, principalment en relació amb la presència de preses, però també com aquesta pot afectar la capacitat d'emmagatzematge dels embassaments i, en conseqüència, la seva viabilitat a llarg termini. Les capçaleres que estan afectades per processos hidro-sedimentaris complexos generen i transporten elevades quantitats de sediments, fet que redueix la capacitat dels embassaments situats més aigües avall. L'**emmagatzematge** temporal de **sediment a la llera** modula el balanç i la distribució d'aquests sediments (ex. riu Isábena). En rius amb baixa activitat geomorfològica, la

reducció de la capacitat d'emmagatzematge dels embassaments degut a l'acumulació de sediments és menor (ex. riu Muga). Els resultats també mostren una alteració hidrològica aigües avall dels embassaments, observable des de nivell diari a anual, tot i que la major alteració s'observa en la magnitud i freqüència de les crescudes. Les preses capturen el sediment i trenquen la continuïtat del seu transport i, a la vegada, els canvis en la **hidrologia** també afecten el règim sedimentari en conjunt. Aigües avall de les preses, s'observa una estabilització de la llera, un fet que s'evidencia amb el cuirassament de la llera i la seva colonització amb **biofilm**, dos processos que incrementen gradualment la competència de cabal necessària per a mobilitzar els sediments i reactivar el dinamisme fluvial. Aquesta tesi il·lustra la dinàmica de l'aigua i els sediments en rius mediterranis, evidencia l'elevat grau d'impacte de les activitats humanes en els processos fluvials i les interaccions bio-físiques, i posa èmfasi en la necessitat d'una **gestió** contínua dels ecosistemes i paisatges mediterranis, que són generalment fràgils, per a obtenir un ús dels recursos hídrics òptim i en consonància amb la preservació dels ecosistemes fluvials.

Paraules clau: hidrologia, transport de sediments, balanç de sediments, embassaments, interacció sediment-biofilm, mesures, experiments, conques mediterrànies

RESUMEN

Los ríos mediterráneos se caracterizan por transportar elevadas cargas de **sedimentos** de forma natural, como consecuencia de la erosión hídrica y la elevada intensidad de los episodios hidro-climáticos (crecidas). Los ríos de esta región presentan una alta variabilidad en su régimen de caudales y, además, están sujetos a elevadas **presiones antrópicas** y a una demanda creciente de agua, que no coincide con la disponibilidad temporal de los recursos hídricos. A causa de este complejo entorno hidro-climático y socio-económico, y con la necesidad de asegurar el suministro de agua, durante la 2ª mitad del siglo XX se construyeron **embalses** de forma generalizada. Además, los cambios en los usos del suelo, principalmente reforestación en las cabeceras de los ríos, han provocado una reducción de la escorrentía y la generación de agua en ríos. Este hecho amenaza el suministro de agua a les partes bajas de la cuenca, donde mayoritariamente se realizan las actividades económicas. Las presas modifican los **flujos de agua y sedimentos** de los ríos, afectando también al funcionamiento de los ecosistemas fluviales. Esta tesis estudia balances de agua y sedimentos en cuencas mediterráneas, así como también procesos fluviales relacionados en ríos naturales y en ríos afectados por impactos antrópicos. El trabajo se llevó a cabo en cuencas situadas al noroeste del mar Mediterráneo, y se escogieron en función de sus características para responder a los objetivos planteados. Por este motivo, se realizó un estudio a escala **multi-temporal** y **multi-espacial**, que incluyó experimentos en canales de laboratorio, medidas de campo y experimentos en tramos de río representativos, así como también el análisis de bases de datos a nivel de cuenca. En general, los resultados muestran la **alteración** de la dinámica hidro-sedimentaria del río, principalmente en relación con la presencia de presas, pero también cómo ésta puede afectar la capacidad de almacenamiento de los embalses y, en consecuencia, su viabilidad a largo plazo. Las cabeceras que están afectadas por procesos hidro-sedimentarios complejos generan y transportan elevadas cantidades de sedimentos, lo que reduce la capacidad de los embalses situados aguas abajo. El **almacenamiento** temporal de **sedimento en el lecho** modula el balance y distribución de estos sedimentos (ej. río Isábena). En ríos con baja actividad geomorfológica, la reducción de

la capacidad de almacenamiento de los embalses debido a la acumulación de sedimentos es menor (ej. río Muga). Los resultados también muestran una alteración hidrológica aguas abajo de los embalses, desde escala diaria a anual, aunque la mayor alteración se observa en la magnitud y frecuencia de las crecidas. Las presas capturan el sedimento y rompen la continuidad de su transporte y, a la vez, los cambios en la **hidrología** también afectan el régimen sedimentario en conjunto. Aguas abajo de las presas, se observa una estabilización del lecho, que se hace evidente con el acorazamiento del lecho y su colonización con **biofilm**, dos procesos que incrementan gradualmente la competencia de caudal necesaria para movilizar los sedimentos y reactivar el dinamismo fluvial. Esta tesis ilustra la dinámica del agua y los sedimentos en ríos mediterráneos, evidencia el elevado grado de impacto de las actividades humanas en los procesos fluviales y las interacciones biofísicas, y pone énfasis en la necesidad de una **gestión** continua de los ecosistemas y paisajes mediterráneos, que son generalmente frágiles, para obtener un uso de los recursos hídricos óptimo y en consonancia con la preservación de los ecosistemas fluviales.

Palabras clave: hidrología, transporte de sedimentos, balance de sedimentos, embalses, interacción sedimento-biofilm, medidas, experimentos, cuencas mediterráneas

CHAPTER 1

Introduction

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BACKGROUND AND RATIONALE OF THE THESIS

Sediment delivery to the oceans

Rivers are responsible of water transport and sediment delivery through the fluvial network, a process that, in the last instance, is the main responsible of the denudational cycle of the continents. The generation of sediments within a river basin occurs mainly in headwaters hillslopes; the amount of sediment depends on several factors such as climate, lithology, and vegetation. Also, the erosion of sediments can be produced by numerous agents, including water. In Mediterranean regions water erosion is spatially the most important erosion process. Eroded sediments are subjected to flow properties and changes, entraining, moving and depositing as a function of flow competence and particle size. The time for sediment particles to complete the travel from the source to the basin outlet cannot be generally established, since sediments can be deposited and stored in the river channel and the floodplains for long periods or permanently (Walling, 1983). The storage period depends on where they are deposited (i.e. main channel, secondary channel, floodplain), as well as on the particle size, magnitude and frequency of floods capable to mobilise sediments, and on the characteristics of the basin (e.g. slope, drainage pattern, vegetation, catchment area; Walling, 1983; Matherne and Prestegaard, 1988). For example, sediments stored in floodplains would only have the possibility to (re)mobilise when a large flood occurs, so they can rest in the floodplains for long periods of time.

Fluvial sediment budgets are constructed to describe and quantify the fluxes of sediments transported from the generation areas to the basin outlet (Slaymaker, 2003). Sediment budgets include all the modes of transport, and also all inputs, outputs and temporal storages. Besides substances that are dissolved in running water, particulate sediments can be transported in different ways, mainly as a function of the particle size. Thus, the smallest particles are usually transported in suspension, whereas coarser particles are transported as bedload. Nevertheless, sediment budgets are often restricted to suspended sediment transport (e.g. Richards, 1982). The utility of sediment budgets can be related, for example, to the establishment of the framework for the study of catchment processes (Parsons, 2012) or to support programmes to prevent and reduce the transport of sediment-borne pollutants (Walling and Collins, 2008).

Sediment transport rates and yields are highly variable since their occurrence is discontinuous at both spatial and temporal scales. The spatio-temporal scale at which these studies are performed is, thus, of great importance and has to be considered when developing and analysing sediment fluxes estimations. Small scales (i.e. reach, catchment) allow the representation and study of isolated and localised cases (e.g. López-Tarazón et al., 2012; Tena et al., 2012). Conversely, broad scales (i.e. regional, worldwide) include more than one study (e.g. Delmas et al., 2009; Vanmaercke et al., 2011), and values are smoothed since average values have to be used in order to eliminate the effects of localised extreme values.

Many studies have assessed sediment budgets or river processes at different spatial and temporal scales (e.g. Carver and Schreier, 1995; Peeters et al., 2008; Cantón et al., 2011). However, relations between scales are still difficult to evaluate, so the extrapolation and upscaling of results is challenging and needs further investigation (Jencso et al., 2009). Cammeraat (2002) pointed out the inter-relations and connections between spatio-temporal scales of analysis in hydro-geomorphic studies, and although present, the linear upscaling is complicated and almost impossible. The high heterogeneity in both spatial and temporal scales is the responsible of the difficult extrapolation at higher scales (Campbell, 1992). This fact can be observed in the wide range of values obtained at broad-scale estimations, since they have been estimated from punctual and isolated studies (despite they are numerous). For instance, the annual sediment delivery to the oceans previous to human alteration was estimated to be of 14 Gt (Syvitski et al., 2005; Walling, 2008), although late 20th century studies were in the range of 15-20 Gt/yr (Vörösmarty et al., 2003). These differences question the sense and goodness of regional and planetary extrapolations.

This thesis is focused on case studies in the western Mediterranean region, where sediment yields are typically above the world mean estimation

(Inbar, 1992; Thornes et al., 2009), probably due to the high rainfall intensity, soil fragility and steep slopes (Poesen and Hooke, 1997). According to Walling and Webb (1983), the higher sediment yields (> 1,000 $t/km^2 \cdot yr$) are located in the Himalaya, the Andes and some points in the North of the Mediterranean Sea and the West coast of the USA. Europe presents a high variability, with values ranging from 'almost negligible' to 500 $t/km^2 \cdot yr$. The region where the study basins of this thesis are located corresponds to an area characterized by sediment yields between 250 and 500 $t/km^2 \cdot yr$, despite local departures from these reference values.

Anthropic effects on water and sediment fluxes

Humans are capable of modifying the transference of water and sediments through river networks. Probably the most visible human modifications of mesoscale Mediterranean natural rivers are both dams and instream mining. Dam construction has direct consequences on both water and sediment loads and fluxes, while mining effects are mostly local and reflected in river morphology. Moreover, there are also other human actions with indirect effects on sediment budgets, as it is the case of land use changes. Figure 1.1 describes the components of sediment budgets in natural systems and the role of the anthropogenic factors that may alter them. The integration of these factors within the budget implies modifications of water and sediment fluxes and, as a consequence, changes are also propagated to the whole ecosystem.

Reservoirs are constructed for multiple purposes (e.g. hydropower generation, flood prevention, irrigation, and urban demands). The number of reservoirs, and their associated storage water capacity, increased progressively during the 20th century, and was especially notable during the second half (1950-1990) of it (Foundation for Water Research, 2010). In semi-arid and arid regions, water availability is very variable within the year and between years, so water storage is crucial to satisfy demands. The number of large dams (higher than 15 m in height according to ICOLD; www.icold-cigb.net) in the world in 2003 was 33,105 with a total storage capacity of 6,700 km^3 ($1\ km^3 = 1\times10^9\ m^3$) a volume that equates almost twice the Lake Huron in the US and Canada, and it is increasing

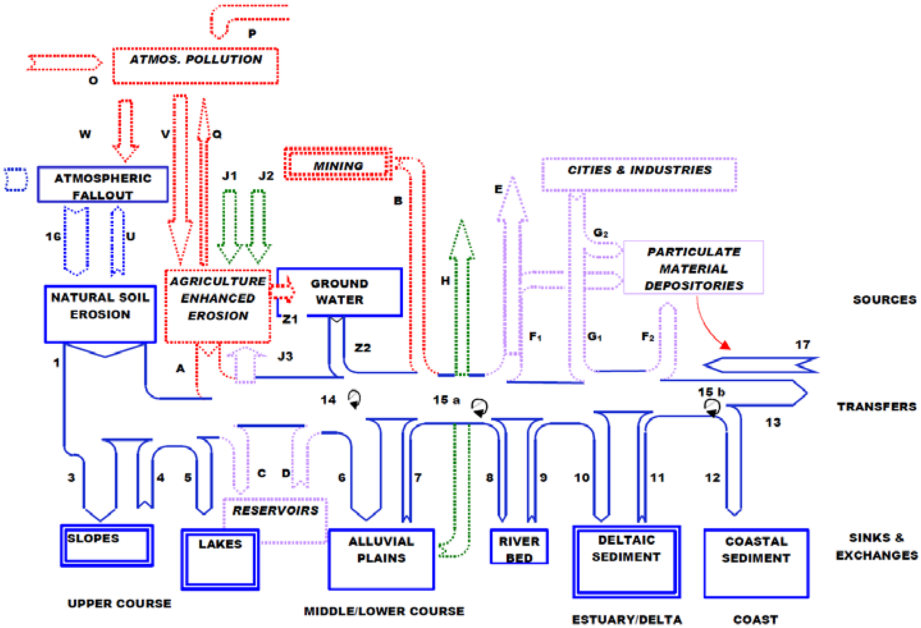

Figure 1.1. Anthropogenic impacts on river matter transfers. #1 to 17: Fluxes in natural systems. #A to Q: fluxes generated within the Anthroposphere. Blue fluxes: mostly natural fluxes. Red fluxes: uncontrolled anthropogenic fluxes. Purple fluxes: controlled anthropogenic fluxes. Green fluxes: fluxes of economic materials. The position of industrial and urban inputs in river catchments is highly variable (from Meybeck et al., 2004).

(Foundation for Water Research, 2010). Figure 1.2 shows the geographical distribution of large dams, and evidences that higher densities of dams are found in mid-latitude basins of the North hemisphere. In Spain (and also France), where this research was carried out, there are more than 1,800 dams already in operation. Although some dams are being currently removed (e.g. the Elwha Dam, US), many other regions are still constructing and planning the construction of large dams (e.g. East Asia, South America; Zarfl et al., 2015). Dam removal has implications downstream, and rivers have to readjust again. To date, observed consequences are related to sudden increases in sediment and nutrients export the first year after removal (Ahearn and Dahlgreen, 2005), and changes in grain size distribution and morphology (Pizzuto, 2002).

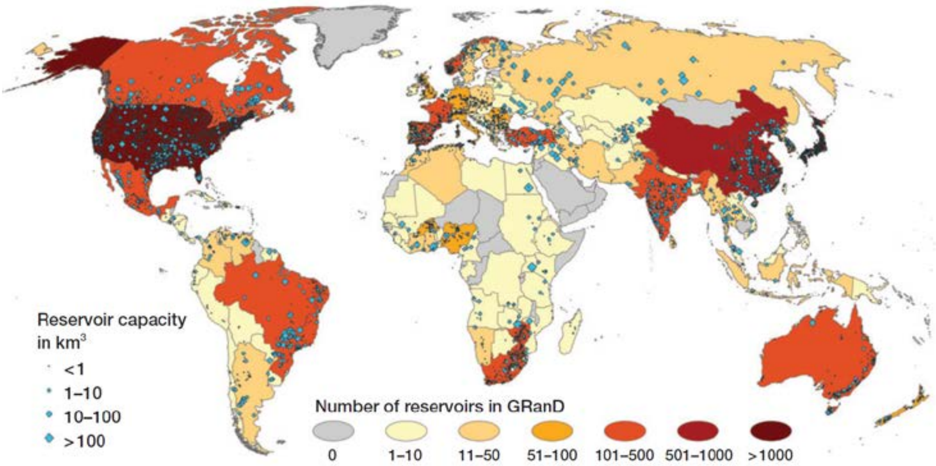

Figure 1.2. Global distribution of large reservoirs (from Lehner et al., 2011).

The entire riverine ecosystem is affected by reservoir presence since it alters the dynamic equilibrium of the river, and the system has to adapt to those changes. Flow regime is altered downstream at daily, monthly and annual scales, mainly reducing its variability and the amount of water released (e.g. Batalla et al., 2004; Magilligan and Nislow, 2005; Lajoie et al., 2009). But the most notable alteration affects flood frequency and magnitude, the elements that control the amount and timing of the mass and energy input into the fluvial system. Rivers morphology, thus habitats, need flows with sufficient competence to mobilise sediments, but the controlled water releases do not usually imply sediment mobilisation, except on large floods or on purpose for economic/ecological reasons (e.g. flushing flows, Batalla and Vericat, 2009; Gomez et al., 2014). It results in the stabilisation of the river bed downstream (Vericat et al., 2006). Additionally, sediment fluxes are cut off and captured in the reservoir, thus generating a sediment deficit downstream (e.g. Vericat and Batalla, 2006; Yang et al., 2007; Tena and Batalla, 2013). The particle size distribution increases downstream from dams (e.g. Kondolf, 1997; Vericat et al., 2008). As a consequence, an armour layer is developed (e.g. Livesey, 1965; Draut et al., 2011), which requires even higher competent flows to mobilise. Ecological changes have been also observed downstream from dams, thus affecting macroinvertebrates and algal communities (e.g. Tonkin and Death, 2013; Ponsatí et al., 2015). Water quality is also altered by river regulation (e.g. Sabater et al., 2009).

In turn, gravel mining has direct geomorphic effects, since the extraction of gravels and sands generate numerous ecological and economic effects. The most evident alterations are changes in channel elevation and in the hydraulic geometry of the channel (Rovira et al., 2005). Sediment removals imply a deficit of sediments downstream the mining area, so the sedimentary equilibrium is altered due to the differences between sediment availability and flow transport capacity, with effects visible both upstream and downstream (Kondolf, 1997). Main changes are related to flow hydraulics (Rinaldi et al., 2005; Rovira et al., 2005), but also to the whole ecosystem, reflected in a loss of habitat and biodiversity (Weeks et al., 2003).

Finally, modifications in basins' land use also produce changes in erosion rates and sediment yields. Studies on this topic exist at basin or regional scales, but not at planetary scale due to the difficulty in estimating and evaluating these changes. Moreover, it could be at some point dispensable given the fact that is continuously changing. The land clearance for agriculture and its intensive use are the main factors that have traditionally produced an increment of sediment yields (Walling, 2008). Conversely, the abandonment of those lands and the regrowth of vegetation caused changes in runoff and sediment loads (e.g. North-eastern Iberian Peninsula, López-Moreno et al., 2007; Buendia et al., 2016).

Syvitski et al. (2005) and Walling (2008) estimated that, after human intervention on ecosystems, the total sediment load delivered to the oceans was of 12.6 Gt/yr. However, other estimates range from 10 to 16 Gt/yr (Vörösmarty et al., 2003). Regarding trapping in reservoirs, Syvitski et al. (2005) and Walling (2008) quantified the reduction caused by reservoir trapping as the 20 and the 66%, respectively, while Vörösmarty et al. (2003) estimated a sediment trapping of almost the 30%. Both estimations show the difficulty in estimations at global scale. At the same time, some human activities also favour sediment delivery to the sea. Dedkov and

Gosarov (2006) quantified the sediment delivered due to anthropogenic activities to be twice that of natural erosion. Nevertheless, other studies showed much lower values (e.g. Syvitski et al., 2005).

Framework of the thesis

The human 'use' of the environment constitutes nowadays the main factor triggering modifications in riverine ecosystems. Among the anthropogenic modifications of river water and sediment loads, this thesis assesses dams' impacts at multiple spatial and temporal scales, since this is one of the main human impacts in the Mediterranean region. Long-term land use changes have been also considered, although in less detail. Specifically, this thesis addresses the changes that dams produce on downstream hydrology, sediment fluxes and the ecosystem. In addition, the effects that natural processes (i.e. large erosion rates in bare areas such as badlands) can generate on rivers sediment budgets and also onto the reservoirs located downstream was also assessed. Figure 1.3 shows the inter-relations between the principal components of sediment budgets that appear in the thesis.

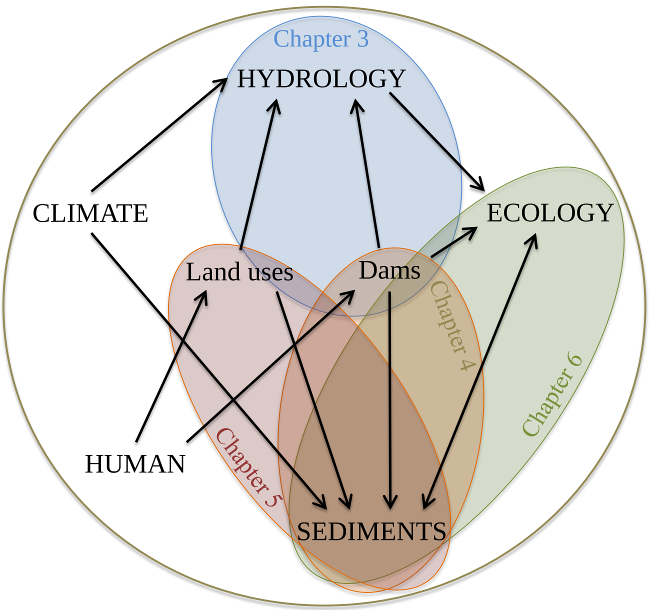

Figure 1.3. Inter-relations between the components of sediment budgets and the factors affecting them that are directly considered in this thesis.

AIM, HYPOTHESES AND OBJECTIVES

Numerous studies have been carried out elsewhere to construct water and sediment budgets of river basins, as well as to evaluate the effects of different impacts on them. Nevertheless, efforts to integrate those budgets at different scales are scarce. Hence, this thesis aims at integrating the findings after assessing a series of multi-scale hydro-sedimentary specific impacts on sediment budgets. Within this context, the **general objective** of the thesis is to analyse the effects of natural processes and anthropic alterations on rivers water and sediment dynamics and budgets. Among the several anthropic impacts, this thesis assesses the role of dams in water and sediments dynamics at different scales. Natural rivers are a continuum from headwaters to the outlet, and the construction of dams generates an abrupt interruption of connectivity between the sediment sources and the oceans to which sediments are delivered. Dams affect the ecosystem at multiple scales, and changes have to be evaluated and quantified to inform subsequent basin management actions.

The main **hypotheses** that direct the work presented in this thesis are:

H1. Dam presence considerably alters the hydrological dynamics of downstream fluvial systems, changing their hydrological regime and reducing the magnitude and frequency of floods; these effects are particularly important in Mediterranean rivers subjected to strong hydro-climatic variability.

H2. Sedimentary river dynamics are conditioned by both anthropic and natural impacts to which catchments are subjected to, thus affecting and modifying the associated sediment budgets and sediment transport processes.

H3. The presence of biofilm affects the structure and surface roughness of the river bed, altering particle entrainment and overall sediment transport processes.

These three working hypotheses are developed through the following **specific objectives**:

O1. To assess the effects of dams on the **hydrology** of Mediterranean rivers.

O2. To evaluate and analyse the **sediment** dynamics of impacted river basins.

O3. To determine the influence of benthic vegetation, i.e. **biofilm,** on river-bed sedimentary processes.

The evaluation of the degree of alteration of hydrological and sedimentary budgets and dynamics after being impacted constitutes an important element for the assessment of river ecosystems health. This information is of especial interest for river basin managers.

STRUCTURE OF THE THESIS

This thesis is presented as a research paper compendium. It is divided in 7 chapters, 4 of which are articles already published (3) submitted (1) in SCI journals (Table 1.1). These four chapters are, thus, organised with the typical structure of research papers, so they can be analysed individually.

Table 1.1. Title, journal and status of the four research articles of the thesis

	Title	Journal	Status
Chapter 3	Hydrological characterization of dammed rivers in the NW Mediterranean region	Hydrological Processes	Published
Chapter 4	The fluvial sediment budget of a dammed river (Upper Muga, Southern Pyrenees)	Geomorphology	Under revision
Chapter 5	Variability of in-channel sediment storage in a river draining highly erodible areas (the Isábena, Ebro Basin)	Journal of Soils and Sediments	Published
Chapter 6	Effects of biofilm on river-bed scour	Science of the Total Environment	Published

The objectives and findings contained in each chapter are contextualised in Figure 1.4 and described in the text below.

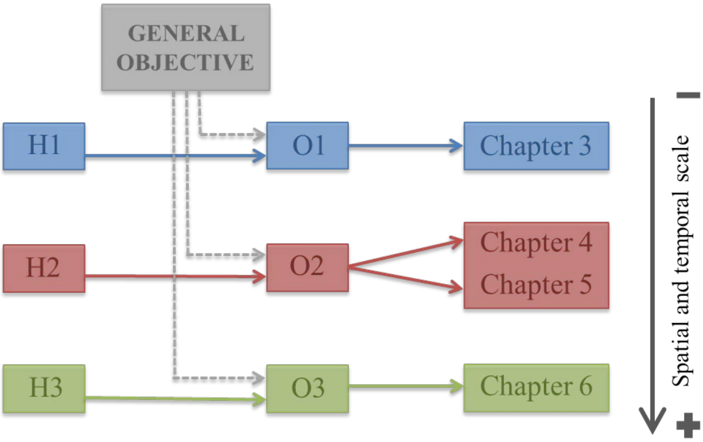

Figure 1.4. Outline of the objectives, hypotheses and the associated chapters that constitute the main body of the present thesis.

Chapter 1 describes the framework of the thesis, thus defining the sediment budget concept and the principal factors that characterise and influence them. This introduction highlights the importance of the study of the sediment dynamics of a basin, as well as the quantification of water and sediment fluxes. **Chapter 2** presents a description of the instruments and methods used to achieve the aims of the thesis. **Chapter 3** corresponds to the first research article, in which the hydrological alteration caused by dam construction was studied at regional scale. Twelve rivers in the north-western Mediterranean region were analysed with this purpose. Chapter 4 and Chapter 5 present two basin sediment budgets, which also correspond to research articles. **Chapter 4** is focused on the River Muga, a mesoscale regulated river that drains directly to the Mediterranean Sea. The total sediment load (i.e. in suspension and bedload) was estimated for three hydrological years (2012-2015). The sediment budget in **Chapter 5** corresponds to the River Isábena. The Isábena is a highly dynamic mesoscale catchment that drains into the Barasona Reservoir. The fine-sediment budget considers the sediments temporarily stored on the river-bed and describes its annual dynamics. **Chapter 6** focuses on the effects of biofilm development on river-bed erosion. The study was carried out in artificial streams (centimetric scale) where the influencing factors could be controlled. The main findings and results obtained in Chapters 3 to 6 were assembled in **Chapter 7**. This final chapter summarises and discusses the relation between water, sediments and dams. The thesis ends with the general conclusions and perspectives for possible future work.

REFERENCES

Ahearn, D.S., Dahlgren, R.A. (2005). Sediment and nutrient dynamics following a low-head dam removal at Murphy Creek, California. *Limnology and Oceanography*, 50 (6): 1752-1762.

Batalla, R.J., Gómez, C.M., Kondolf, G.M. (2004). Reservoir-induced hydrological changes in the Ebro River basin (NE Spain). *Journal of Hydrology*, 290: 117-136.

Batalla, R.J., Vericat, D. (2009). Hydrological and sediment transport dynamics of flushing flows: Implications for management in large Mediterranean rivers. *River Research and Applications*, 25: 297-314.

Buendia, C., Bussi, G., Tuset, J., Vericat, D., Sabater, S., Palau, A., Batalla, R.J. (2016). Effects of afforestation on runoff and sediment load in an upland Mediterranean catchment. *Science of the Total Environment*, 540: 144-157.

Cammeraat, L.H. (2002). A review of two strongly contrasting geomorphological systems within the context of scale. *Earth Surface Processes and Landforms*, 27 (11): 1201-1222.

Campbell, I. (1992). Spatial and temporal variations in erosion and sediment yield. In: *Erosion and Sediment Transport Monitoring Programmes in River Basins. Proceedings of the Oslo Symposium.* IAHS Publications, 210: 455-466.wall

Cantón, Y., Solé-Benet, A., de Vente, J., Boix-Fayos. C., Calco-Cases, A., Asensio, C., Puigdefábregas, J. (2011). A review of runoff generation and soil erosion across scales in semiarid south-eastern Spain. *Journal of Arid Environments*, 75 (12): 1254-1261.

Carver, M., Schreier, H. (1995). Sediment and Nutrient Budgets over Four Spatial Scales in the Jhikhu Khola Watershed: Implications for Land Use Management. In: Brown, S., Schreier, H., Shah, P.B. (eds): *Challenges in mountain resource management in Nepal: processes, trends and dynamics in middle mountain watersheds*. Proceedings of Workshop: 155-162. International Research Centre, Ottawa.

Dedkov, A.P., Gusarov, A.V. (2006). Suspended sediment yield from continents into the World Ocean: spatial and temporal changeability. In: *Sediment Dynamics and the Hydromorphology of Fluvial Systems*. IAHS Publications, 306: 3-11.

Delmas, M., Cerdan, O., Mouchel, J.M., Garcin, M. (2009). A method for developing large-scale sediment yield index for European river basins. *Journal of Soils and Sediments*, 9 (6): 613-626.

Draut, A.E., Logan, J.B., Mastin, M.C. (2011). Channel evolution on the dammed Elwha River, Washington, USA. *Geomorphology*, 127 (1-2): 71-87.

Foundation for Water Research (2005, updated 2010). *World water: Resources, usage and the role of man-made reservoirs.* FR/R0012, Marlow, United Kingdom.

Gomez, C.M., Pérez-Blanco, C.D., Batalla, R.J. (2014). Tradeoffs in river restoration: Flushing flows vs. hydropower generation in the Lower Ebro River, Spain. *Journal of Hydrology*, 518: 130-139.

Inbar, M. (1992). Rates of fluvial erosion in basins with a Mediterranean type climate. *Catena*, 19 (3-4): 393-409.

Jencso, K.G., McGlynn, B.L., Gooseff, M.N., Wondzell, S.M., Bencala, K.E., Marshall, L.A. (2009). Hydrological connectivity between landscapes and streams: Transferring reach- and plot-scale understanding to the catchment scale. *Water Resources Research*, 45: W04428.

Kondolf, G.M. (1997). Hungry Water: Effects of Dams and Gravel Mining on River Channels. *Environmental Management*, 21 (4): 533-551.

Lajoie, F., Assani, A.A., Roy, A., Mesfioui, M. (2009). Impacts of dams on monthly flow characteristics. The influence of watershed size and seasons. *Journal of Hydrology*, 334: 423-439.

Lehner, B., Liermann, C.R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J.C., Rödel, R., Sindorf, N., Wisser, D. (2011). High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Frontiers in Ecology and the Environment*, 9 (9): 494-502.

Livesey, R.H. (1965). Channel armoring below Fort Randall Dam. *Proceedings of the Federal Inter-Agency Sedimentation Conference*, Miscellaneous Publication No. 970, Agricultural Reserach Service.

López-Moreno, J.I., Beguería, S., García-Ruiz, J.M. (2006). Trends in high flows in the central Spanish Pyrenees: response to climatic factors or to land-use change? *Hydrological Sciences Journal*, 51 (6): 1039-1050.

López-Tarazón, J.A., Batalla, R.J., Vericat, D., Francke, T. (2012). The sediment budget of a highly dynamic mesoscale catchment: The River Isábena. *Geomorphology*, 138 (1): 15-28.

Magilligan, F.J., Nislow, K.H. (2005). Changes in hydrologic regime by dams. *Geomorphology*, 71: 61-78.

Matherne, A.M., Prestegaard, K.L. (1988). Hydrological characteristics as a determinant of sediment delivery in watersheds. *Proceedings of the Porto Alegre Symposium*, IAHS Publications, 174: 89-96.

Meybeck, M., Duerr, H., Vogler, J., Lachartre, L., Guéguen, Y. (2004). Space analysis of catchment/coast relationship. Synthesis report: European catchments, catchment changes and their impact on the coast, 'EuroCat', European Commission, DG Research. 5th Framework Programme, Contribution No. EVK1-CT-2000-00044

Parsons, A. (2012). How useful are catchment sediment budgets? *Progress in Physical Geography*, 36 (1): 60-71.

Peeters, I., Van Oost, K., Govers, G., Verstraeten, G., Rommens, T., Poesen, J. (2008). The compatibility of erosion data at different temporal scales. *Earth and Planetary Science Letters*, 265 (1-2): 138-152.

Pizzuto, J. (2002). Effects of Dam Removal on River Form and Process. *BioScience*, 52 (8): 683-691.

Poesen, J.W.A., Hooke, J.M. (1997). Erosion, flooding and cannel management in Mediterranean environments of southern Europe. *Progress in Physical Geography*, 21 (2): 157-199.

Ponsatí, L., Acuña, V., Aristi, I., Arroita, M., García-Berthou, E., von Schiller, D., Elosegui, A., Sabater, S. (2015). Biofilm responses to flow regulation by dams in Mediterranean rivers. *River Research and Applications*, 31 (8): 1003-1016.

Richards, K. (1982). *Rivers: Form and Process in Alluvial Channels*. Methuen, 358 pp.

Rinaldi, M., Wyzga, B., Surian, N. (2005). Sediment mining in alluvial channels: Physical effets and management perspectives. *River Research and Applications*, 21: 805-828.

Rovira, A., Batalla, R.J., Sala, M. (2005). Response of a river sediment budget after historical gravel mining (the lower Tordera, NE Spain). *River Research and Applications*, 21 (7): 829-847.

Sabater, S., Muñoz, I., Feio, M.J., Romaní, A.M., Graça, M.A.S. (2009). The Iberian Rivers. In: Tockner, K., Uehlinger, U., Robinson, C.T. (eds): *Rivers of Europe*. Elsevier Science and Technology, Amsterdam.

Slaymaker, O. (2003). The sediment budget as conceptual framework and management tool. *Hydrobiologia*, 494: 71-82.

Syvitski, J. P. M., Vörösmarty, C. J., Kettner, A. J., Green, P. (2005). Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science*, 308: 376-380.

Tena, A., Batalla, R.J., Vericat, D. (2012). Reach-scale suspended sediment balance downstream from dams in a large Mediterranean river. *Hydrological Sciences Journal*, 57 (5): 37-41.

Tena, A., Batalla, R.J. (2013). The sediment budget of a large river regulated by dams (The lower River Ebro, NE Spain). *Journal of Soils and Sediments*, 13 (5): 966-980.

Thornes, J., López-Bermúdez, F., Woodward, J. (2009). Hydrology, River Regimes, and Sediment Yield. In: Woodward (ed): *The Physical Geography of the Mediterranean*. Oxford University Press, Oxford Regional Environments Series, 704 pp.

Tonkin, J.D., Death, R.G. (2014). The combined effects of flow regulation and an artificial flow reléase on a regulated river. *River Research and Applications*, 30 (3): 329-337.

Vanmaercke, M., Poesen. J., Verstraeten, G., de Vente, J., Ocakoglu, F. (2011). Sediment Yield in Europe: Spatial patterns and scale dependency. *Geomorphology*, 130 (3-4): 142-161.

Vericat, D., Batalla, R.J. (2006). Sediment transport in a large impounded river: The lower Ebro, NE Iberian Peninsula. *Geomorphology*, 79 (1-2): 72-92.

Vericat, D., Batalla, R.J., Garcia, C. (2006). Transporte de fondo y dinámica sedimentaria en un río altamente regulado: el bajo Ebro (NE Península Ibérica). *Revista Brasilera de Geomorfología*, 7 (2): 39-49.

Vericat, D., Batalla, R.J., Garcia, C. (2008). Bed-material mobility in a large river below dams. *Geodinamica Acta*, 21 (1-2): 3-10.

Vörösmarty, C.J., Meybeck, M., Fekete, B., Sharma, K., Green, P., Syvitski, P.M. (2003). Anthropogenic sediment retention: major global impact from registered river impoundments. *Global and Planetary Change*, 39: 169-190.

Walling, D.E. (1983). The sediment delivery problem. *Journal of Hydrology*, 65: 209-237.

Walling, D.E. (2008). The changing sediment loads of the world's rivers. *Annals of Warsaw University of Life Sciences* – SGGW, Land Reclamation, 39: 3-20.

Walling, D.E., Webb, B.W. (1983). Patterns of sediment yield. In: Gregory, K.J. (ed): *Background to Palaeohydrology*, 69-100. Wiley, Chichester.

Walling, D.E., Collins, A.L. (2008). The catchment sediment budget as a management tool. *Environment Science and Policy*, 11: 136-143.

Weeks, J.M., Sims, I., Lawson, C., Harrison, D.J. (2003). River Mining: assessment of the ecological effects of river mining in the Rio Minho and Yallahs rivers, Jamaica. *British Geological Survey Commissioned Report*, CR/03/162N, 53 pp.

Yang, S.L., Zhang, J., Xu, X.J. (2007). Influence of the Three Gorges Dam on downstream delivery of sediment and its environmental implications, Yangtze River. *Geophysical Research Letters*, 34, L10401.

Zarfl, C., Lumsdon, A.E., Berlekamp, J., Tydecks, L., Tockner, K. (2015). A global boom in hydropower dam construction. *Aquatic Science*, 77: 161-170.

CHAPTER 2

Methods

Photo: Ramon J. Batalla

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INTRODUCTION

This chapter describes the methods and techniques applied to achieve the objectives of the thesis, the functioning of the principal instruments and sensors used, and data post-processing and treatment to obtain final values. The chapter is organised chronologically by the different steps needed to obtain the final data: i.e. from data acquisition in the field and laboratory post-processing, to statistical treatment and data analysis. The methods exposed can be later dealt with in more detail in each specific chapter (Chapters 3 to 6).

Figure 2.1. is included in this chapter with a twofold intention: i) organise the research chapters of the thesis in the correct spatial and temporal scales at which they have been assessed, and ii) classify the monitored issues and the principal methods used in this spatio-temporal frame of the thesis. Hence, the figure summarises and encompasses the ensemble of temporal scales, spatial scales, study areas and methods used in each chapter. The outputs that resulted from each study are also included in the figure. The combination and addition of the three specific objectives results in the response of the general objective.

The first aim of the figure (i) is shown in the larger graph. The spatial scale, which ranges from centimetres to kilometres, facilitated the achievement of the objectives previously established. Temporal scales were mainly determined by the minimum time needed to achieve the objectives or by data availability. The methods were chosen in function of the spatial and temporal scales used in the thesis. Similarly, the study area was different in every chapter, in order to properly assess the objectives established. Hence, the figure ensembles all this information and emplaces it in its correct position in the graph, thus relating both spatial and temporal scales.

With the aim to also specify the scale of work and the methods used (ii), the different issues being monitored are represented in separate smaller spatio-temporal graphs, where the scale of work has been highlighted. These graphs show that some issues were measured by different approximations and methods depending on the scale of work.

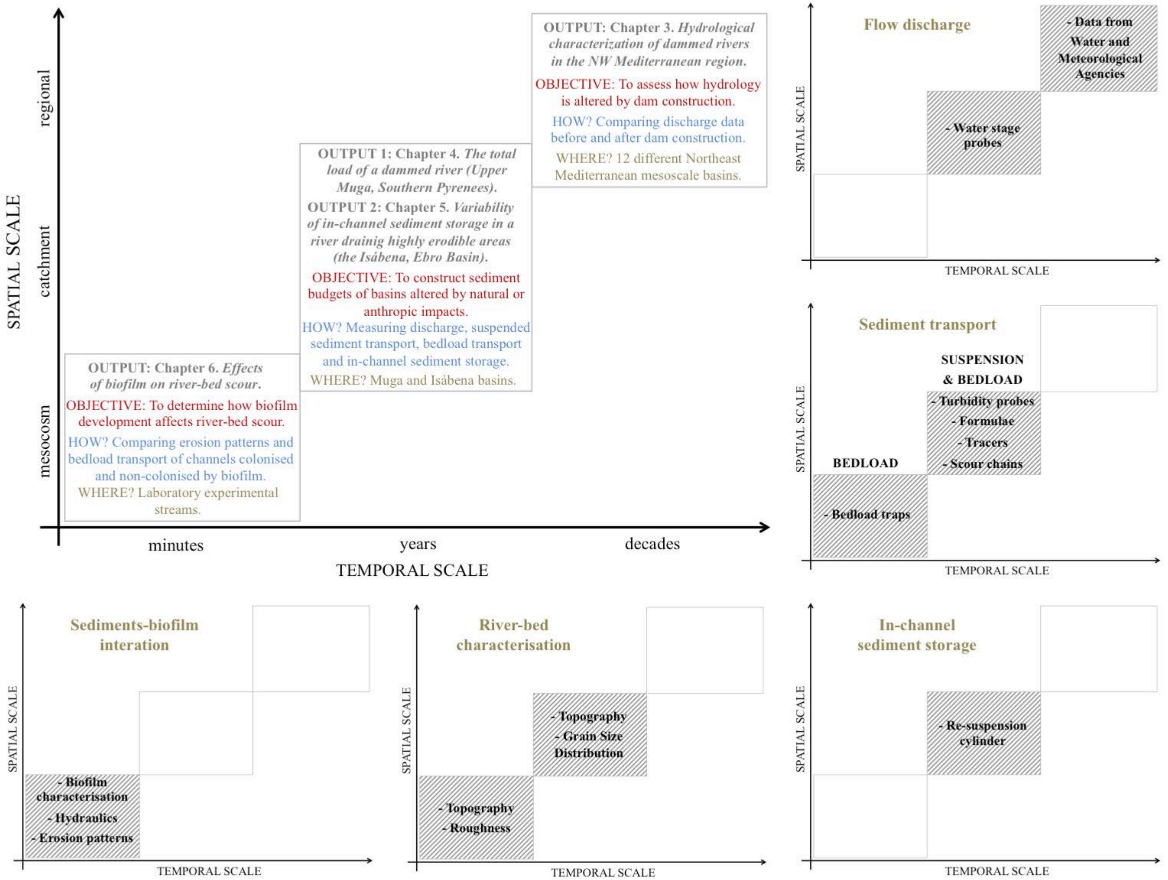

Figure 2.1. Principal descriptors of the work carried out in the thesis, organised as a function of the temporal and spatial scales of work.

DATA ACQUISITION

Data compilation

Flow discharge data

Data for the long-term hydrological analysis (Chapter 3) were obtained from two different official institutions. Data from the inner Catalan basins were given by the Catalan Water Agency (ACA), while data from French catchments were downloaded from the Banque Hydro webpage (www.hydro.eaufrance.fr) of the French Government. Finally, data from the River Isábena (Chapter 5) were obtained from the Ebro Water Authorities (CHE).

Precipitation data

Precipitation data series were used in Chapter 3 to assess temporal trends from mid 20th century. Data were provided by the Agencia Estatal de Meteorología and Météo-France, the former provided data for the Catalan basins and the latter for the Southern France ones. Likewise, precipitation data from the Isábena and neighbouring basins that appears in Chapter 5 were obtained from the Ebro Water Authorities.

Land use data

Land cover maps were used to complement the information given by hydrological data in Chapter 3. They were obtained from the Coordination of the Information on the Environment (CORINE) database, which includes the countries of the European Union. Land cover rasters have a cell resolution of 100 × 100 m, and (at the time the paper was prepared) were available for the years 1990 and 2012. Maps can be downloaded from the European Environmental Agency webpage (http://www.eea.europa.eu).

Field and laboratory work

Flow stage

For a more detailed temporal scale analysis (i.e. at the annual span) and to study basin sedimentary budgets, water stage probes were installed at selected monitoring stations of the studied rivers (Chapters 4 and 5). Two types of sensors were used: i) pressure sensors (Solinst®, Figure 2.2a), and ii) capacitive sensors (TruTrack® WT-HR, Figure 2.2b). The output of capacitive sensors was directly the height of the water column. However, pressure sensors needed both the pressure of the water column on the sampling point and the air pressure, so two probes were used. To obtain the height of the water column, air pressure was subtracted from the water pressure and converted to millimetres of water.

Figure 2.2. a) Example of pressure water stage sensors and installation; b) Example of capacitive water stage sensor and installation.

Suspended sediment concentration

Suspended sediment was measured and estimated at catchment and annual scales to construct the sedimentary budgets of two very different basins (Chapters 4 and 5). Two methods were used: i) isolated sampling of sediment transported in suspension, and ii) continuous turbidity registers with OBS probes.

i) In order to obtain good estimations of suspended sediment transport, a high number of samples were collected during base flows, high flows and floods. Water samples were collected as close as possible to the turbidity probes by means of automatic samplers, water stage samplers or manually (Figure 2.3). Automatic samplers were activated at early stages of floods, in order to sample both the rising and recession limbs of the flood. Water stage samplers (WSS) were successively filled as water level rose, so samples corresponded exclusively to the rising limb. They were designed to avoid water recirculation, so once the bottles were filled, no 'new' water could replace the existing.

Figure 2.3. a) Automatic sampler ISCO® 3700 (Photo: J.A. López-Tarazón); b) Water stage sampler. Both were used to calibrate turbidity sensors and models.

Samples were subsequently post-processed in the laboratory to obtain the real concentration of sediment transported in suspension at a given time. Hence, water samples were filtered through 1.2 µm pore size microfiber filters or decanted when suspended sediment concentration was high (Figure 2.4). At the same time, the water volume was also measured (usually between 0.5 and 1 l).

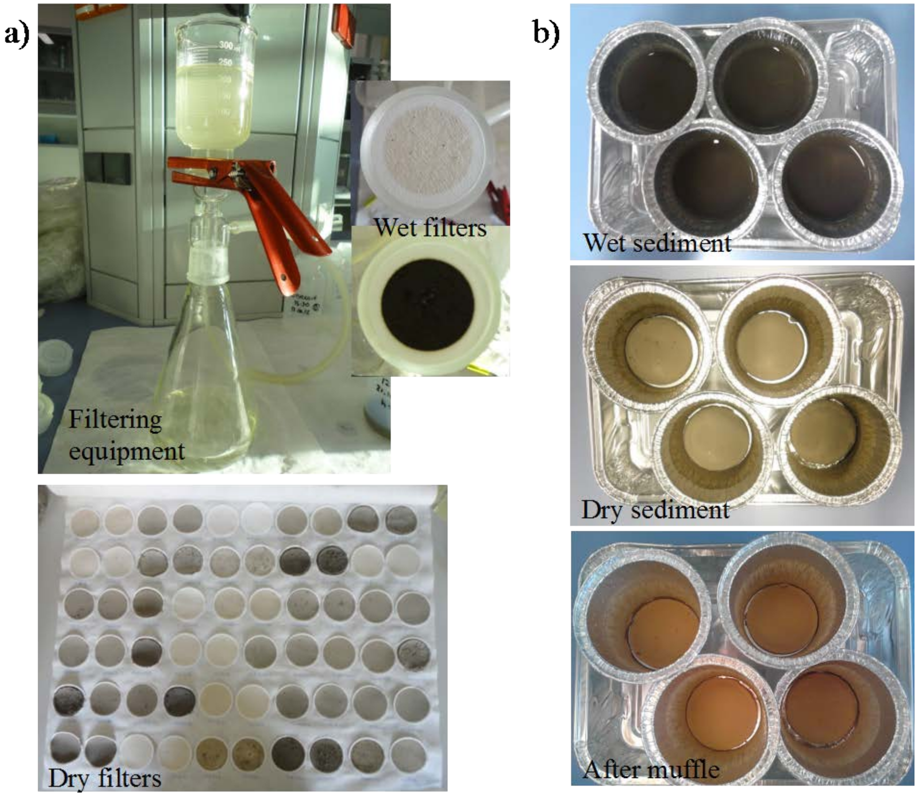

Figure 2.4. a) Filtering equipment and examples of wet and dry filters after processing; b) Examples of sediment after decanting in aluminium jars.

Sediment was subsequently dried in the oven and later combusted at 450ºC for 4 hours to eliminate organic matter, and thus obtain the weight of the inorganic sediment and the organic matter separately. The net weight of sediment in the filter or jar and the volume of water that was filtered allowed the calculation of the suspended sediment concentration (*SSC*).

ii) Continuous water turbidity records were obtained by OBS probes (Optical Backscatter Sensors), often called turbidimeters or turbidity probes, connected to dataloggers (Figure 2.5). These instruments were used both in the Muga and Isábena basins (Chapters 4 and 5), and were installed at official gauging stations from the water authorities and programmed to record a turbidity value every 15 minutes.

Figure 2.5. a) Example of Campbell® turbidity probe installed in a gauging station; b) Campbell® OBS 3+ probe (Font: www.campbellsci.com/obs-3plus); c) Example of turbidity probe installation.

<u>In-channel sediment storage</u>

The sediment being temporarily stored on the river bed was quantified at catchment scale in the River Isábena (Chapter 5) by means of the resuspension cylinder (Lambert and Walling, 1988). The cylinder is a piece of stainless steel of 0.6 m height and 0.5 m of diameter, with a foam rubber at the bottom part to facilitate the adjustment to the irregular river bed (Figure 2.6). The cylinder diameter corresponds to the sampling area, while the height permits the calculation of the volume of water being sampled. Once the cylinder is placed onto the river bed and rotated to prevent water and sediment losses, sediments are disturbed with a rod to resuspend the available sediment.

Three levels of disturbance were performed: i) no disturbance, so two samples of current water were taken to be treated as a blank, ii) water was agitated and two samples taken, and iii) water and the upper 10 cm of the river bed sediments were agitated, and two samples were taken. Water samples were subsequently filtered or decanted in the laboratory, following the procedure described in the previous section. A minimum of three samplings were carried out at each site to account for cross-sectional variability.

Figure 2.6. Resuspension cylinder used for in-channel sediment quantification.

Bed-material mobility

Bedload transport was estimated by means of indirect methods with the aim to validate the results obtained by equations. Both painted tracers and radio-frequency tagged tracers were installed on the river bed for gravel-bed rivers (Figure 2.7a and b). These methods could not be applied for sand rivers. Painted areas allow the identification of the whole range of particle sizes present in the river bed without disturbing its structure, but cannot be recovered if they are buried or spun after a flood. In turn, tracers tagged with RFID (Radio Frequency Identification) are restricted to coarse particles and do not maintain river bed structure, but buried particles can be recovered. The exact position of tracers was identified when installed and, after a flood, tracers were found again to measure the distance that moved during the episode. In the thesis, tracers were used at catchment scale in the River Muga (Chapter 4). Two painted areas were installed in gravel-bed study reaches, while RFID were only used upstream the reservoir.

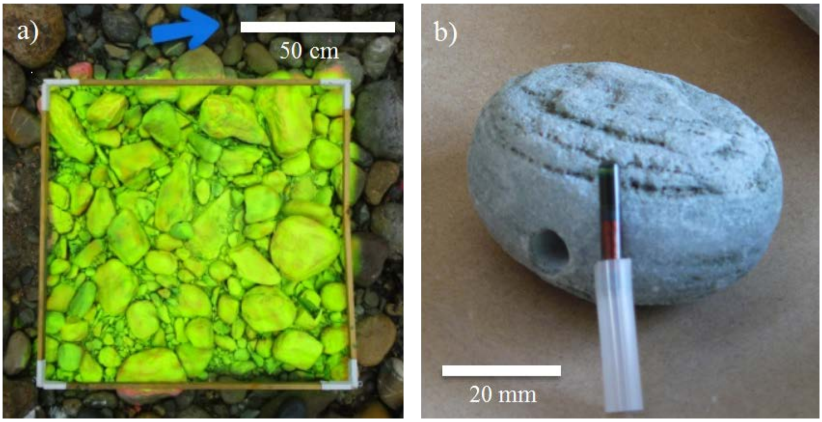

Figure 2.7. a) Painted tracers; b) Cobble tagged with RFID.

Scour chains were used in order to estimate the depth of the active layer for given floods. For this, chains were anchored and buried vertically within the gravels and sands of the river bed, leaving some centimetres of chain on the bed in the flow direction. After a flood, the visible length of the chain and its configuration (i.e. buried or not, depth, etc.) were compared to the chain configuration before the flood. This comparison informed about the scour and fill processes that occurred during the flood. More details on the information given by the scour chains can be found in e.g. Hassan (1990) or Houbrechts et al. (2012). Scour chains were installed in the gravel-bed study reach upstream the dam in the River Muga (Chapter 4).

Figure 2.8. Scour chain installed in the field.

Topography

Topographic surveys were carried out using three different instruments: i) GNSS smart antenna Leica® Viva GS15 (GPS), ii) Total Station TPS Leica® TS02 and iii) Terrestrial Laser Scanner Leica® ScanStation C10 (TLS, Figure 2.9). The GPS (i) works with GNSS technology and permits fast acquisition of high precision data. However, it does not work properly with dense riverine vegetation. Working with TPS (ii) is slower, but it permits surveying narrow rivers covered by riverine trees. TLS (iii) are based on LiDAR technology, and are high resolution and precision instruments (i.e. between 25,000 to 50,000 observations per second; and millimetre precision). In the present thesis, GNSS smart antenna and TPS were used when river channel cross-sections were needed for further calculations (Chapters 4 and 5), and samplings were carefully done trying to represent slope breaks. The TLS was used when continuous bed elevation data was required (Chapter 6).

Figure. 2.9. a) GPS; b) Total Station, TPS; c) Terrestrial Laser Scan, TLS.

Grain size distribution (GSD)

The measurement of the river bed particle sizes was carried out to characterise the river bed and to calculate its roughness coefficient for the application of bedload transport formulae (Chapter 4). Distinct methods were used for the characterisation of the river bed material, in function of the size of the sediments and whether it was surface or subsurface material

(Figure 2.10). For gravel-bed rivers, surface GSD was determined by the pebble count procedure (Wolman, 1954). A minimum of 200 particles were sampled, measurements were carried out with a template to facilitate rapid *b*-axis measurement. The subsurface material was sampled using the volumetric method. The coarser fractions were sieved *in situ* using a field gravelometer, while particles with *b*-axis < 22.6 mm were taken to the laboratory. After drying, those sediments were sieved using a Filtra® FLT-0200 sieves' shaker. For sand rivers, no differentiation could be done between surface and subsurface material, so samplings were done according to the volumetric method. Pebble count and volumetric methods results are directly comparable, with no need of conversion. For both methods, particle size classes were determined by ½ φ Wentworth scale.

Figure 2.10. a) Surface and subsurface material; b) Field equipment: Wolman pebble count template and portable gravelometer (Photo: R.J. Batalla); c) Laboratory equipment: Sieve's shaker.

Experimental work

The role of biofilm on the sediment stability was assessed at centimetre scale. The use of the mesocosms (stream channels) allowed analysing the sediment mobility while not disrupting the biofilm, a challenge extremely difficult in the field.

The experiments were performed at the Experimental Streams Facility of the Catalan Institute for Water Research (Chapter 6). Twelve of the channels of the mesocosm facility (2 × 0.1 × 0.1 m) were colonised by means epipsammic biofilm that was allowed to grow for 5 weeks. Biofilm inocula was obtained from the nearby River Llémena, and added to the channel five times in the first two weeks. Sediment patches colonised by biofilm were taken from the river to the laboratory, where biofilm was 'separated' from sediment particles and filtered (Figure 2.11a-d). A mixture of nutrients (i.e. P and N) was added daily to the water. Environment conditions were kept to facilitate biofilm growth: air temperature between 22 and 24 ºC, 12-12 h of daily light/dark cycles, low and constant discharge (i.e. 30 ml/s), and the minimum slope possible (0.5%).

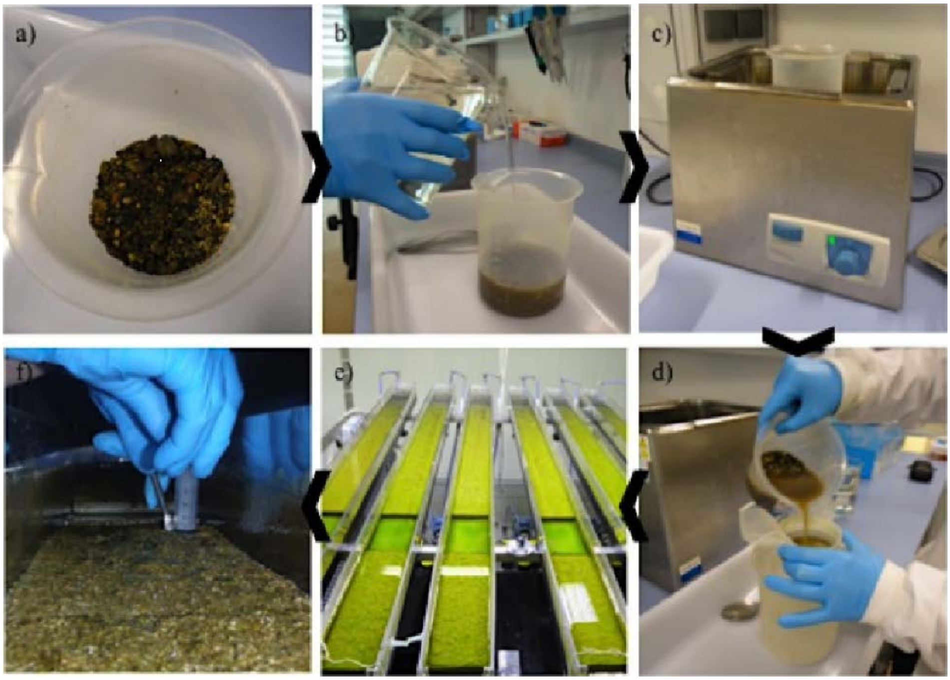

Figure 2.11. a-d) Procedure to obtain inoculum from epipsammic biofilm; e) Biofilm-colonised channels before the experiments; f) Biofilm samples collection with a syringe.

For biofilm sampling (Figure 2.11f), an untapped syringe was used to collect sediment colonised with biofilm. In total, twelve samples per channel were taken and used to quantify total biomass, algal biomass and extracellular polymeric substances, as well as to identify the principal algal groups that form the biofilm.

For the experiments defining the sediment-biofilm interaction, channels were configured as shown in Figure 2.11e. As such, each of the channel was divided in 3 parts:

I) Sediments for sediment-biofilm interaction measurements (120 cm length).
II) Free-sediments reach (20 cm) to place the bedload microtraps during experimental runs.
III) Sediments for biofilm samples collection (40 cm).

The extremes of the channels (both upstream and downstream) were left without sediments in order to facilitate water inflow and outflow without disturbing the sediments placed in the bed.

Before and after the experimental runs, a high-precision survey of the channel bed was obtained using a Terrestrial Laser Scan (TLS, Figure 2.12a, and also described in previous sections). During the experiments, both hydraulics (i.e. flow velocity, water depth) and bedload transport rates were measured. The former were measured using a current meter (Figure 2.12b) and a standard ruler, respectively; while the latter was measured using a bespoke bedload trap at the end of the measurement area (Figure 2.12c). Bedload traps consisted of boxes without cover placed in the channel, waiting for episodes of particle mobility. When discharge reached the particle entrainment threshold, sediments being transported fell into the traps. The amount of sediment transported could be calculated by the dry weight of sediment trapped.

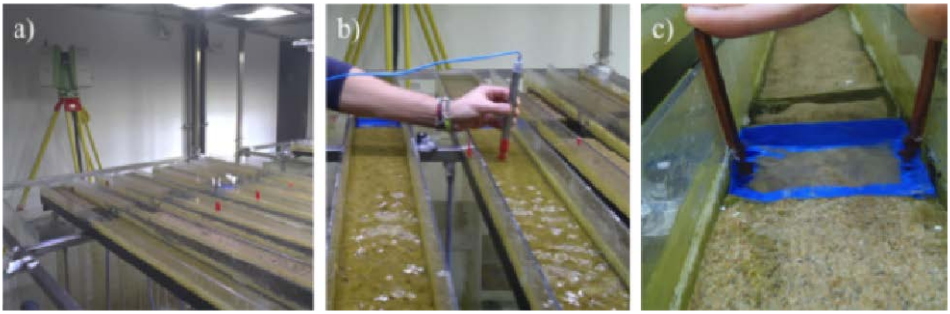

Figure 2.12. a) Terrestrial Laser Scanner located at the end of the channels; b) Current meter; c) Bedload microtrap.

DATA ANALYSIS

Data treatment and modelling

Flow discharge

Flow discharge data at regional and long-term scales were statistically analysed to establish simple comparison between the conditions before dam construction and conditions after dam construction. The alteration of flow discharges at different temporal scales, as well as the changes in magnitude and frequency of floods were described, following the study performed by Batalla et al. (2004). Additionally, an analysis using the Indicators of Hydrological Alteration (IHA) software program was carried out. The IHA software (version 7.1)[1] was developed by *The Nature Conservancy* (TNC) with the aim to facilitate analysis and comparison between hydrological components before and after human alteration.

At basin and annual scales, data from the water stage probes were used. Probes were calibrated with real observations of water stage (i.e. regressions between measured stage *vs.* observed stage; Figure 2.13a) to correct measured values. Water stage values were later transformed into

[1]https://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/MethodsandTools/IndicatorsofHydrologicAlteration/Pages/indicators-hydrologic-alt.aspx)

discharge by means of stage-discharge (i.e. *h*/*Q*) rating curves. Where possible, the official rating curves from gauging stations were used. Where inexistent, they were obtained by modelling using WinXSPRO® or HEC-RAS software (see further sections for more details on software functioning). The values of *h* and *Q* obtained by modelling were correlated to obtain *h*/*Q* rating curves specific for each site (Figure 2.13b). The regressions were applied to continuous water stage data, thus obtaining flow discharge values.

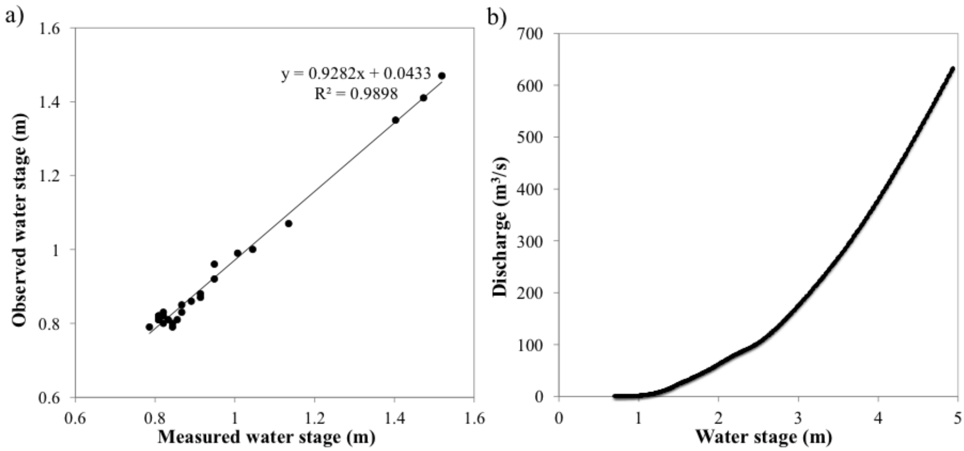

Figure 2.13. a) Regression between measured and real water stage for Muga's EA050 gauging station; b) Official *h*/*Q* rating curve for Muga's EA050 gauging station ceded by the Catalan Water Agency.

When missing *Q* data, gaps were filled by estimation with data from neighbouring sub-basins. Thus, regressions between flow discharges of the two sub-basins were established. If significant correlation occurred, the equation was used. This procedure was used to fill the gaps in two sub-basins in Chapter 4.

Suspended sediment transport

Suspended sediment concentration was calculated after the filtering or decantation of water samples (method described in previous sections) by the application of the following equation:

Eq. 2.1 $$SSC = \frac{(W_{Sed} - W_{OM})}{V_{Water}}$$

where, SSC is Suspended Sediment Concentration (mg/l), W_{Sed} is the weight of the total dry sediment (i.e. organic + inorganic, in mg), W_{OM} is the weight of the organic matter (mg), and V_{water} is the water volume in the sample (l).

SSC values corresponded to punctual instants in time, and were used for the estimation of continuous records of *SSC* by the use of: i) transformation of turbidity measurements into sediment loads, ii) *Q-SSC* rating curves, and iii) modelling. These three methods were applied in different parts of the thesis with the aim to obtain continuous sedigraphs for suspended sediment, in function of the study and instrumentation availability.

i) Punctual *SSC* observations were correlated with turbidity readings, and the resulting regression equation was applied to the continuous turbidity records. This method was applied in Chapter 4 and 5, where OBS probes were used. *Turbidity-SSC* relations followed a linear regression:

Eq. 2.2 $$SSC = a \times Turb \pm b$$

where $Turb$ is the turbidity value measured by OBS probes (in mV), and a and b are coefficients. Figure 2.14 shows an example of the relation between OBS measurements and *SSC*.

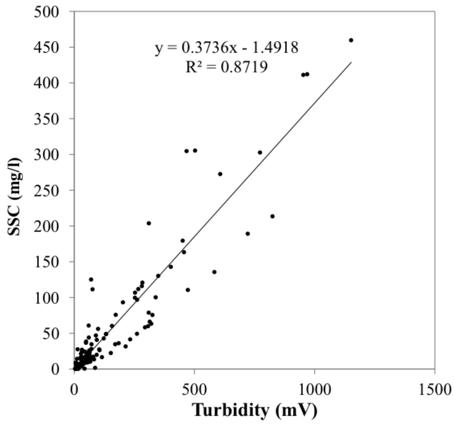

Figure 2.14. Relation between OBS measures (mV) and observed *SSC* used for the calibration of the OBS probe at Muga's site EA050.

ii) *Q*-*SSC* rating curves method consisted in the application of the regression equation between *Q* and *SSC* for each individual monitoring station to flow discharge values. This method was applied only to the River Muga, when turbidity records were not available (Chapter 4). It was not possible to use it in the River Isábena due to the low correlation between *Q* and *SSC* values. Although usually power-law relations are the most appropriate for *Q*-*SSC* relations (Syvitski et al., 2000), the ones used in the River Muga followed a linear relation (i.e. same as Eq. 2.2 but changing *Turb* for *Q*) since its R^2 correlation coefficient was higher, and also significant. In one occasion, two linear regressions were used in order to adjust the most as possible to data distribution. Figure 2.15 shows an example of *Q*-*SSC* relations used to extend *SSC* registers. For a further in-deep description on how missing suspended sediment data was obtained see Chapter 4.

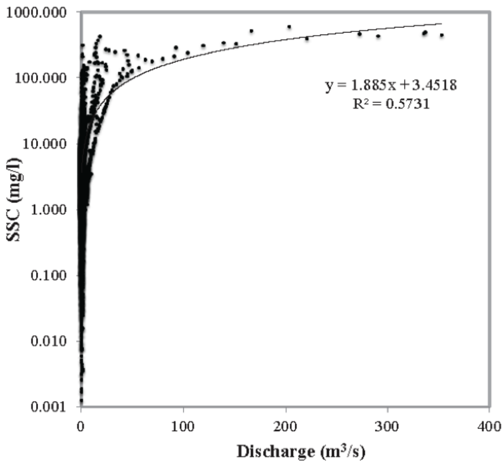

Figure 2.15. Relation between *Q* and observed *SSC* used for the *SSC* estimations at the Muga site EA050.

iii) Modelling was used in the Isábena (Chapter 5). The statistical techniques Random Forest and Quantile Regression Forest (RF and QRF respectively; Breiman, 2001; Meinshausen, 2006) were applied to model *SSC* in the sub-basins where data were not available. RF and QRF are tree-based, non-parametric techniques that give good results in predicting sedimentary data, and have been applied in the River Isábena in previous studies yielding satisfactory results (e.g. Francke et al., 2008; López-Tarazón et al., 2012; Buendia et al., 2016). The modelisation of these data was obtained in the frame of the SESAM project (Sediment Export from Large Semi-Arid Catchments: Measurement and Modelling), and the computation of these sedigraphs was carried out and published by Francke et al. (2104).

Precipitation

Long-term precipitation data for Catalan and French basins were statistically analysed by means of the Mann-Kendall statistic to assess the trends in (approximately) the last 60 years (Chapter 3). The use of this statistic is appropriate for the analysis of not normally distributed data series. The existence of trends was, thus, evaluated by the *p*-value of the trend value given by the τ coefficient.

Land use changes

The differences in land cover were calculated in Chapter 3 with the objective to complement the hydrological analyses. The aim of the analysis was to assess the differences in land cover between the years 1990 and 2006. The percentage of change obtained per each land use and basin was obtained as:

Eq. 2.3 $$\%\, land\ use\ change\ = \frac{(land\_use_{2006} - land\_use_{1990})}{land\_use_{1990}} \times 100$$

Topography

Cross-sections surveyed by GPS and TPS needed subsequently data post-processing to correct and determine the exact coordinates of cross-sections. Coordinates corrections were performed by the Leica® Geo Office software by means of RINEX data downloaded from the Institut Cartogràfic i Geològic de Catalunya and the Instituto Geográfico Nacional.

The point clouds obtained from the TLS surveys in experimental streams had to be also post-processed in order to obtain (i) Digital Elevation Models (DEM), (ii) roughness maps, and (iii) statistics of each individual cell used for erosion quantification. First, point clouds were cut with the shape of the channel and transformed into regular cells by means of ToPCAT algorithm (Brasington et al., 2012), and statistics calculated for each cell. Hence, DEMs (i) were developed from the minimum elevation within each cell, (considered the channel bed elevation), and roughness maps (ii) were developed from the standard deviation of the detrended elevations (considered as the value that defines the variability of the bed elevations within a cell).

River bed roughness

Roughness coefficient is needed for river-bed characterisation and hydraulic and h/Q calculations (see previous sections for more details).

Data obtained by grain size distribution measurements was used to calculate river bed roughness (n) by means of the Strickler (1923) roughness coefficient:

Eq. 2.4 $$n = 0.0151 \times (D_{50})^{1/6}$$

where D_{50} is the median value of the grain size distribution.

Roughness values for the experimental streams were calculated from the statistics of each cell, as explained in the previous section.

Hydraulics

Hydraulic parameters (as radius, water depth and active channel width) were used for both the calculation of h/Q rating curves (Chapters 4 and 5) and bedload transport rates (Chapter 4). In the two cases, hydraulic parameters were estimated by modelling with WinXSPRO® and HEC-RAS software. These two software use topographic (i.e. cross-sections) and roughness (from GSD measurements) data to simulate increments in water stage or discharge, respectively, and then calculate hydraulic parameters corresponding to these increments. Both software applications base their stage or discharge calculations on the Manning's equation, which is expressed as:

Eq. 2.4
$$V = \frac{\left(R^{2/3} \times S^{1/2}\right)}{n}$$

where V is flow velocity (m/s), R is hydraulic radius (m), S is slope (dimensionless) and n is the roughness coefficient (dimensionless).

Sediment loads estimation

Suspended sediment transport

Continuous suspended sediment load records were needed for sediment budget calculations in Chapters 4 and 5. Continuous registers of Q and *SSC* were the basis for this calculation, which was obtained by multiplying the amount of water (in l) that circulated in the river for a given period (usually 15 min) by the *SSC* (mg/l) being transported for the same period. The sum of the resulting 15-min loads (mg) allow for the calculation of monthly/seasonal/annual suspended sediment loads.

Bedload transport

Bedload transport was calculated for the Upper River Muga (Chapter 4) by means of bedload formulae. Those formulae were chosen according to river bed characteristics, mainly regarding grain size distribution of the river bed material (roughness). Thus, in gravel-bed rivers, bedload transport was estimated by Bathurst (2007) and Recking (2010) formulae, both of them designed for armoured rivers. For the sand river studied, bedload equations did not report reliable results, and bedload transport was estimated using values from similar rivers located in the north-western Mediterranean region. Worth to note that bedload formulae estimate the transport capacity of a river and do not consider the likelihood of rivers to be supply-limited, so estimations may overestimate the real bedload transport. For their application, the equations require some fluvial hydraulic geometry parameters (e.g. hydraulic radius, active width) and particle size statistics (i.e. median, percentiles). Those parameters were obtained from river cross-sections and grain size distribution (GSD) analysis (see previous sections for more details).

For total bedload computation, bedload transport rates (usually in $m^3/s\cdot m$ or $kg/s\cdot m$) were multiplied by the channel width and the seconds of a given period of time. Again, the sum of the resulting loads (kg) allow for the calculation of the monthly/seasonal/annual bedload.

In-channel sediment storage

The sediment stored within each cross-section area was calculated as the average of the sampling points of the section, multiplied by the width of the channel. Average values were used in order to account for the in-channel variability of the section and smooth the values.

Finally, the total values of each section were extrapolated for the total length of the study reach (i.e. ~38 km) to obtain an estimation of the amount of sediment stored on the river bed at a given time. The extrapolation was done per river stretches between sections, calculated as the average sediment storage of the upstream and downstream sections multiplied by the stretch length.

REFERENCES

Batalla, R.J., Gómez, C.M, Kondolf, G.M. (2004). Reservoir-induced hydrological changes in the Ebro River basin (NE Spain). *Journal of Hydrology*, 290: 117-136.

Bathurst, J.C. (2007). Effect of Coarse Surface Layer on Bed-load Transport. *Journal of Hydraulic Engineering*, 133 (11): 1192-1205.

Brasington, J., Vericat, D., Rychkov, I. (2012). Modelling river bed morphology, roughness and surface sedimentology using high resolution terrestrial laser scanning. *Water Resources Research*, 48 (11): W11519.

Breiman, L. (2001). Random Forests. *Machine Learning*, 45: 5-32.

Buendia, C., Vericat, D., Batalla, R.J., Gibbins, C.N. (2016). Temporal dynamics of sediment transport and transient in-channel storage in a highly erodible catchment. *Land Degradation & Development*, 27: 1045-1063.

Francke, T., López-Tarazón, J.A., Schröder, B. (2008). Estimation of suspended sediment concentration and yield using linear models, random forest and quantile regression forests. *Hydrological Processes*, 22: 4892-4904.

Francke, T., Werb, S., Sommerer, E., López-Tarazón, J.A. (2014). Analysis of runoff, sediment dynamics and sediment yield of subcatchments in the highly erodible Isábena catchment, Central Pyrenees. *Journal of Soils and Sediments*, 14 (12): 1909-1920.

Hassan, M. A. 1990. Scour, fill, and burial depth of coarse material in gravel bed streams. *Earth Surface Processes and Landforms*, 15: 341-356.

Houbrechts, G., Van Campenhout, J., Levecq, Y., Hallot, E., Peeters, A., Petit, F. (2012). Comparison of methods for quantifying active layer dynamics and bedload discharge in armoured gravel-bed rivers. *Earth Surface Processes and Landforms*, 37 (14): 1501-1517.

Lambert, C.P., Walling, D.E. (1988). Measurements of channel storage of suspended sediment in a gravel-bed river. *Catena*, 82: 23-34.

López-Tarazón, J.A., Batalla, R.J., Vericat, D., Francke, T. (2012). The sediment budget of a highly dynamic mesoscale catchment: the River Isábena. *Geomorphology*, 138: 15-28.

Meinshausen, N. (2006). Quantile Regression Forests. *Journal of Machine Learning Research*, 7: 983-999.

Recking, A. (2010). A Comparison between Flume and Field Bed Load Transport Data and Consequences for Surface Based Bed Load Transport Prediction. *Water Resources Research*, 46 (3): W03518.

Strickler, A. (1923). Beiträge zur Frage der Geschwindigheitsformel und der auhigkeitszahlen für Strome, Kanale und Geschlossene Leitungen. *Mitteilungen des Eidnössischer Amtes für Wasserwirtschaft*, Bern, Switzerland, 16 pp.

Syvitski, J. P., Morehead, M. D., Bahr, D. B., Mulder, T. (2000). Estimating fluvial sediment transport: The rating parameters. *Water Resources Research*, 36 (9): 2747-2760.

Wolman, M.G. (1954). A method of sampling coarse bed material. *American Geophysical Union Transactions*, 35: 951-956.

CHAPTER 3

Hydrological characterization of dammed rivers in the NW Mediterranean region

Photo: Ramon J. Batalla

Piqué, G., Sabater, S., Batalla, R.J. (2016). Hydrological characterization of dammed rivers in the NW Mediterranean region. *Hydrological Processes*, 30 (11): 1691-1707.

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ABSTRACT

Water scarcity and climatic variability in the Mediterranean region have traditionally required the construction of dams to guarantee water supply for irrigation, industrial and urban uses and hydropower production. Reservoirs affect the hydrology of the river downstream, but the magnitude and persistence of these effects are still poorly unknown. Understanding the magnitude of these effects is the objective of this paper, in which we analyse the flow regimes of twelve rivers located in the NW Mediterranean region. Different temporal scales (daily, monthly and annual) are used for the analysis and also to estimate flow variables associated with flow magnitude, frequency, duration and variability. It is shown that dams alter the hydrological regime of most of the studied rivers, with special influence on monthly flows and flood magnitude and frequency. The most altered rivers (Muga and Siurana, NE Iberian Peninsula) experience a complete overturn in their flow regime with, for instance, flood reduction reaching up to 76% for the 2-year flood event. Other rivers showed lower changes in hydrology (e.g. Orb and Têt). Annual runoff showed a pattern of decrease in all the studied rivers (regulated and non-regulated) indicating that besides dams (i.e. reservoir evaporation), other factors likely affect water yield. A general recovery downstream from dams is also observed at all temporal scales, mainly because of the inflow from tributaries. Although dams have a clear impact on the hydrology of Mediterranean rivers, water withdrawals and diversions for irrigation and other consumptive uses also affected the hydrological patterns.

KEYWORDS fluvial hydrology, dams, flow regulation, Mediterranean basin

INTRODUCTION

Mediterranean regions must cope with water scarcity and spatial and temporal heterogeneous distribution of water resources. Water scarcity is related to the irregular distribution of precipitation throughout the year, being concentrated in winter months (Eastern and Southern parts of the Mediterranean basin) or in spring and autumn (Western region), but is also related to the very high water demand (Barceló and Sabater, 2010). Such a scarcity has favoured intensive dam construction in order to guarantee water supply for irrigation and urban or industrial uses in the region. Dam construction has been intensive especially during the second half of the 20th century (Beaumont, 1978; Beaumont, 1993). Those areas showing more dams are the most water-thirsty, especially in the Mediterranean (e.g. Cooper et al., 2013).

Dams alter the hydro-sedimentary regime downstream (i.e. water discharge and sediment load; e.g. Williams and Wolman, 1984; Batalla et al., 2004) and have effects on the functioning of fluvial ecosystems (Ward and Stanford, 1979; Aristi et al., 2014; Ponsatí et al., 2014). River regulation decreases the magnitude and frequency of floods, annual runoff is altered and seasonal and daily distribution of flows changes downstream from reservoirs, having large effects on the river ecology (Petts, 1984; Belmar et al., 2010). One major consequence of flow interruption is the alteration in the continuity of sediment transport (both in suspension and bedload), which causes long-term accumulation of sediments in the reservoirs, as well as sedimentary disequilibrium on the river channel downstream (Kondolf, 1997). This alters both the hydro-sedimentary dynamics of the river (e.g. Batalla et al., 2006) and is associated with the erosion of deltas (Milliman, 2001). Because the entire flow range is ecologically important (Mathews and Richter, 2007), the ecological connectivity between floodplains and channels is also compromised (Kondolf, 1997). While flood events are important to facilitate dispersion and colonization of potential habitats (Nislow et al., 2002), low flow periods are relevant to essential biological and biogeochemical processes in the river (Sabater et al., 2008).

Quantifying the degree of hydrological alteration caused by dams may allow both a better understanding of river ecosystems response as well as improving reservoir management and river-restoration practices. Identifying such impacts requires careful definition of the hydrological regimes before and after the existence of dams, and this can be performed by the examination of long-term data series. Different software tools may be used for this purpose; for instance, the Index of Hydrologic Alteration (hereafter IHA) summarizes the hydrological variability between years, providing useful comparison of present flow regimes (i.e. after regulation) with the natural flow regimes (Mathews and Richter, 2007). The IHA also includes environmental flow components (EFC) that allow classifying discharge in categories related to flow conditions, ranging from extremely low flows to large floods (Mathews and Richter, 2007).

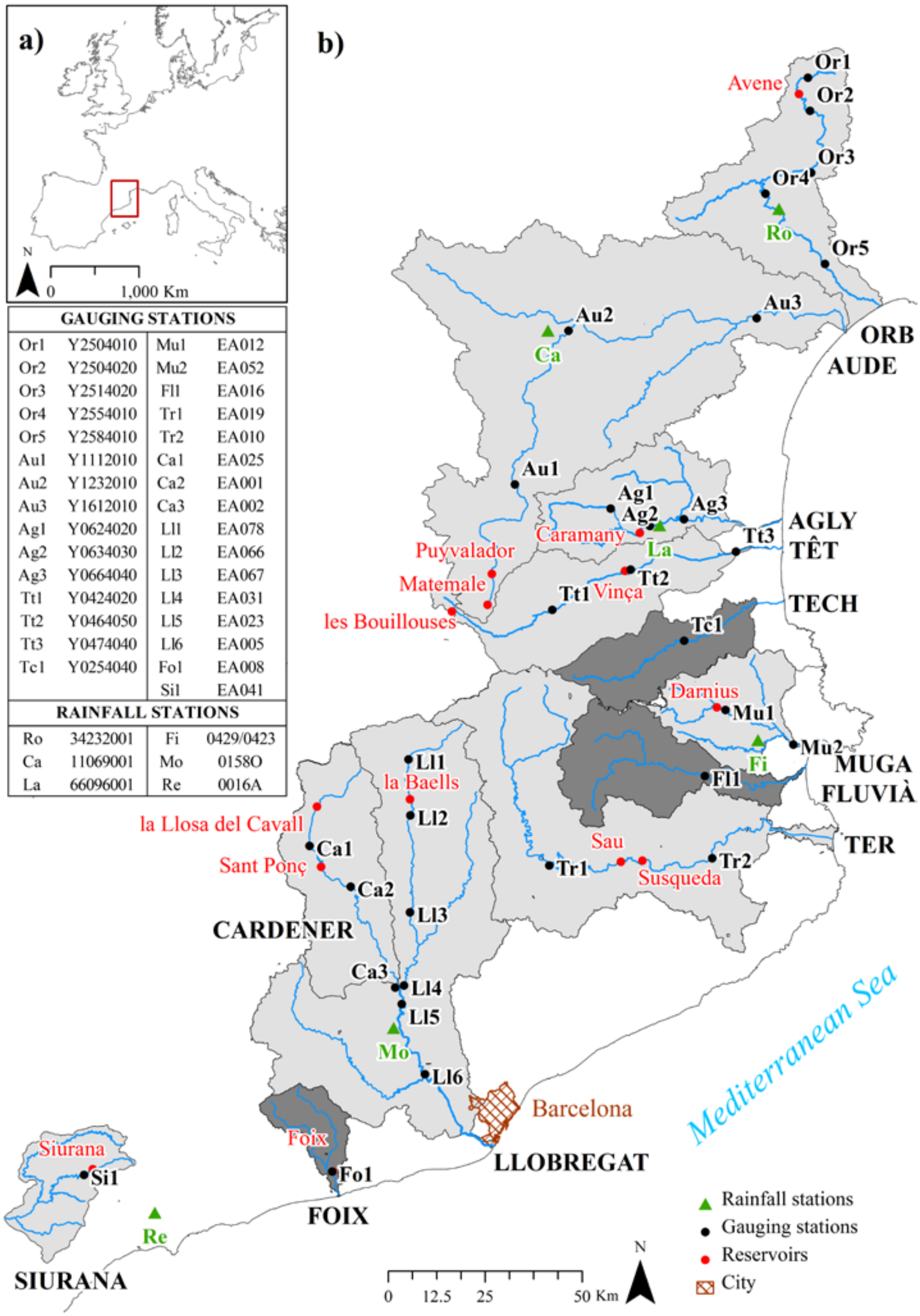
Both regional-based and local-based factors may contribute to the definition of hydrological patterns downstream from reservoirs. These encompass climatic factors at varying scales as well as management-derived decisions on water flow. This type of analysis requires the use of added hydrological analysis of several river data, so it might transcend the detailed analysis of single river regimes. The aim of this paper is to characterize the effects of large dams on the hydrology of selected rivers of the Western Mediterranean region. Under this context, the specific objectives are as follows: (i) to determine the effects of reservoirs in water flow downstream and (ii) to evaluate the persistence of alterations caused by dams in the magnitude and frequency of floods and in the whole hydrological regime. We specifically aim to understand how much tributaries inflow contributes to river recovery downstream by weakening the effects of dams. We therefore focus on whether the recovery downstream has the same pattern in all the rivers or if it is also related to other factors (such as catchment size, degree of impoundment and latitudinal gradient). Because of the regional approach scale of this work, we have restricted the analysis to large reservoirs, and the model of analysis can be considered a black box model because it does not consider water diversions and operational rules of the reservoirs.

STUDY AREA

Twelve basins located in the western area of the Mediterranean Sea were selected for the analysis, encompassing rivers located north and south of the Pyrenean Range. From north to south, they are the Orb, Aude, Agly, Têt and Tech in the South of France; and the Muga, Fluvià, Ter, Llobregat mainstem, Cardener, Foix and Siurana in the northeast of the Iberian Peninsula (Figure 3.1). Ten of these rivers are regulated by large dams, whereas the other two are not regulated (i.e. Tech and Fluvià) and are considered to have a natural flow regime.

All the studied rivers were characterized by warm, dry summers and mild winters, and wet springs and autumns. Goossens (1985) characterized the studied basins by having most rainfall during the first half of the year and very little in summer. Inside this particular region, mean annual precipitation does not depend on the latitudinal gradient but differs considerably from one basin to the neighbouring mostly because of orographic effects (Wainwright and Thornes, 2004). All basins have similar longitudinal patterns of precipitation, with maxima in the headwaters and a gradual decrease towards the mouth. Mean annual rainfall ranges from 760 mm in Roquebrun (Ro in Figure 3.1) to 523 mm in Reus (Re in Figure 3.1). These sites were also characterized by high rainfall variability; Reus was the driest rainfall station, with mean annual precipitation ranging from 250 to 975 mm, while Roquebrun and Latour-de-France (Ro and La in Figure 3.1, respectively) were the most humid, ranging from 333 to 1,500 mm.

Basin surface areas ranged from 300 km^2 to more than 5,000 km^2, and reservoir size spanned from 10 to 233 hm^3 of capacity (Table 3.1). The majority of dams were built in the second part of the 20th century, mainly during the late 1960s and 1970s. Reservoirs respond to water storage for irrigation, urban uses, hydropower electricity generation and flood prevention uses, although in more recent years, also leisure activities gained importance. Larger reservoirs (capacity > 100 hm^3) are la Baells, Sau and Susqueda, located in the Llobregat and Ter. Apart from large reservoirs, rivers have many weirs (usually few meter high) that can also have a



GAUGING STATIONS			
Or1	Y2504010	Mu1	EA012
Or2	Y2504020	Mu2	EA052
Or3	Y2514020	Fl1	EA016
Or4	Y2554010	Tr1	EA019
Or5	Y2584010	Tr2	EA010
Au1	Y1112010	Ca1	EA025
Au2	Y1232010	Ca2	EA001
Au3	Y1612010	Ca3	EA002
Ag1	Y0624020	Ll1	EA078
Ag2	Y0634030	Ll2	EA066
Ag3	Y0664040	Ll3	EA067
Tt1	Y0424020	Ll4	EA031
Tt2	Y0464050	Ll5	EA023
Tt3	Y0474040	Ll6	EA005
Tc1	Y0254040	Fo1	EA008
		Si1	EA041

RAINFALL STATIONS			
Ro	34232001	Fi	0429/0423
Ca	11069001	Mo	0158O
La	66096001	Re	0016A

Figure 3.1. a) Location of the NW Mediterranean basins in Europe and b) location of the study basins and the gauging stations used for the analysis. Light grey basins are used to assess regulation impacts, while dark grey basins are the non-regulated ones.

regulation effect during lower flows, and some basins have water diversions, withdrawals and by-passes to guarantee water demands.

METHODS

Daily flow data series for the rivers Muga, Fluvià, Ter, Cardener, Llobregat, Foix and Siurana were provided by the Catalan Water Agency (ACA), whereas data from the Orb, Aude, Agly, Têt and Tech were downloaded from the Banque Hydro webpage of the French Government (original data from the DREAL Languedoc-Roussillon/ HYDRO-MEDDE/DE and the DDAF Pyrénées-Orientales/ HYDRO-MEDDE/DE). Dams and gauging stations were selected to reflect hydrologic alterations produced by reservoirs and its persistence downstream, though the location of the stations and the number of years with available data were the determinants for selecting the gauging stations. Finally, 31 data series were analysed. Impoundments with a water storage capacity less than 3 hm^3 were not considered in the analysis because of their lower regulation capacity, especially on floods. Three of the rivers have been used as references (i.e. Tech, Fluvià and Foix). Among them, the Tech and Fluvià are not regulated by large dams (although they have small reservoirs and weirs of less than 2 hm^3 of capacity); the Foix has a large dam in the lowermost part of the basin, so the upstream reach was only considered to assess non-regulated flows.

Two different series of gauging stations, respectively located upstream and downstream of dams were used in most cases. The same number of years upstream and downstream was analysed in order to have analogous natural climatic influences. In three rivers (i.e. Aude, Muga and Siurana), data series upstream from reservoirs were too short or inexistent. In these cases, data series of stations immediately downstream from dams were divided in two periods (i.e. pre-dam *vs*. post-dam), in order to reflect the periods before and after the dam construction. In the non-regulated rivers (Tech, Fluvià and Foix), only data from one gauging station were analysed, and the series were considered representative for the respective areas. Results are therefore presented for altered (i.e. upstream or pre-dam) and non-altered

Table 3.1. Principal characteristics of the studied dams and data series (see Figure 3.1 for location details).

	Reservoir	Year	Capacity (hm^3)	Resevoir uses	Gauging stations	Drainage area (km^2)	Non-altered series WY	Non-altered series n	Altered series WY	Altered series n
Regulated										
ORB	Avène	1965	33.6	I, F, U, H	Y2504010	85	1967-1991	8	-	-
					Y2504020	185	-	-	1967-1991	8
					Y2514020	369	-	-	1968-1991	7
					Y2554010	905	-	-	1968-1991	7
					Y2584010	1,330	-	-	1967-1991	8
AUDE	Matemale + Puyvalador	1960 1932	20.5 9.9	H H	Y1112010	692	1914-1932	18	1932-1960	21
									1960-2014	48
					Y1232010	1,770	-	-	1969-2014	42
					Y1612010	4,836	-	-	1969-1994	24
AGLY	Caramany	1995	25.8	I, F, U, L	Y0624020	216	1996-2013	17	-	-
					Y0634030	440	-	-	1996-2013	14
					Y0664040	903	-	-	1996-2013	15
TÊT	(Bouillouses) + Vinçà	1910 1978	17.3 24.6	I, L I, F, U	Y0424010	424	1977-2002	25	-	-
					Y0464050	974	-	-	1977-2002	22
					Y0474040	1,371	-	-	1977-2002	25
MUGA	Darnius Boadella	1969	61.1	I, F, U, H	EA012	191	1912-1969	46	1969-2011	34
					EA052	756	-	-	1969-2011	30
TER	Sau-Susqueda	1962 1968	151.3 233	I, F, U, H	EA019	1,386	1986-2011	24	-	-
					EA010	2,265	-	-	1986-2011	19
CARDENER	(La Llosa del Cavall) + Sant Ponç	1997 1957	80 24.4	U U, H	EA025	248	1957-1993	31	-	-
					EA001	650	-	-	1957-1993	36
					EA002	1,339	-	-	1957-1993	36
LLOBREGAT	La Baells	1976	109.5	I, F, U, H	EA078	333	1976-2011	33	-	-
					EA066	538	-	-	1976-2011	24
					EA067	1,022	-	-	1976-2011	35
					EA031	1,888	-	-	1976-1999	21
	LaBaells + StPonç				*EA023*	3,327	1945-1957	12	1958-1976	17
									1976-1993	17
					EA005	4,577	1945-1957	12	1957-1976	19
									1977-1993	17
SIURANA	Siurana	1971	12	I, U	EA041+C4042	86	1953-1971	18	1971-1999	28
Non-regulated										
TECH	-	-	-	-	Y0254040	473	1967-2004	37	-	-
FLUVIÀ	-	-	-	-	EA016	804	1912-2003	79	-	-
FOIX	-	-	-	-	EA008	288	1943-2010	55	-	-

I, Irrigation; F, Flood prevention; U, Urban or industrial; H, Hydroelectric production; L, Leisure

In ( ), reservoirs not included in the analysis because non-altered data was not available.

Data in italics correspond to data series used to assess recovery downstream.

sites (i.e. downstream or post-dam), to minimize potential confusion. In all of the cases, only complete hydrological years were used (i.e. years with high number of missing data were excluded).

In order to assess the potential hydrological recovery or persistence downstream, data were also analysed for gauging stations as close as possible (when available) to the river outlet. The recovery was defined as the river capacity to re-establish similar hydrological pre-dam conditions with distance downstream.

Five of the studied rivers are regulated by one large reservoir, but the rivers Aude, Têt, Ter and Cardener are regulated by two large dams. When possible (i.e. the Aude), the effect of the impoundment was analysed separately to assess the impact of each specific reservoir. The River Têt has les Bouillouses Dam constructed in 1910, but discharge measurements were not available neither previously nor upstream of the reservoir. In the River Cardener, la Llosa del Cavall Dam was constructed in 1997, and only a few years of data were available after its construction. Hence, les Bouillouses and la Llosa del Cavall reservoirs were not considered for the analysis. Finally, dams on the River Ter were built close to each other, and therefore, the reservoirs were analysed as a single entity (i.e. dams' chain).

Precipitation data

Historical rainfall data series of six meteorological stations were analysed by means of the Mann-Kendall statistic with the objective to determine whether or not a significant trend existed in the temporal data series. The Mann-Kendall test (Kendall, 1975; Mann, 1945) is a non-parametric test, which allows the statistical analysis for data that are not normally distributed. The test was applied to selected precipitation data series located close to the studied rivers and distributed across the region from north to south: Roquebrun, Carcassonne, Latour-de-France, Figueres, Montserrat and Reus (Figure 3.1). Data from Roquebrun, Carcassonne and Latour-de-France were provided by Météo-France, and data from Figueres (a combination between Peralada and Figueres rainfall stations), Montserrat and Reus were obtained from the Agencia Estatal de Meteorología

(AEMET). All stations have at least 59 years of complete data, beginning between 1945 and 1951, with the exception of Montserrat, which began on 1971 and has thus 39 years of complete data.

To assess the degree to which precipitation changes influenced the variations in runoff, the method used by Yang et al. (2015) was reproduced for the Muga basin, as a representative basin for the whole set of studied basins. The precipitation data of the Muga basin were part of the gridded dataset developed by the AEMET and the Santander Meteorology Group (University of Cantabria-CSIC). This derived from interpolated daily data of more than 2,000 meteorological stations with the result of a 20-km horizontal resolution grid that covers the peninsular Spain and the Balearic Islands (Herrera et al., 2010). The three points in the gridded dataset that correspond to the Muga headwaters (upstream the reservoir) were selected, and data averaged to obtain a single precipitation data series. Further, the correlations between annual precipitation and water yield (hereafter WY) before dam construction (1951-1969 time period) were established and used to compare with the observed pre-dam and post-dam values (1969-2007 time period) (Yang et al., 2015). The impact of precipitation was determined as the difference between the predicted WY and the pre-dam measured WY, while the impact due to other factors was quantified as the difference between the predicted WY and the post-dam measured WY.

Land use changes analysis

The evaluation of land use changes in the basins was performed using available raster Land Cover maps from the Coordination of Information on the Environment (CORINE) database. The CORINE Land Cover map was available for the years 1990 and 2006; the map of 2012 does not cover yet the whole Iberian Peninsula. Thus, the total number of years in this analysis was 16. To facilitate comparison, land uses were reclassified into six general classes: agriculture, grassland and scrubland, woodland, improductive, urban and water.

Impacts in magnitude and frequency of floods

The Impounded Runoff index (hereafter IR after Batalla et al., 2004) has been used as an indicator of the degree of change of water flow due to reservoirs. This index can be taken as a proxy of the mean residence time of the water in the reservoir, but it is normally used as a non-dimensional index of the degree of impoundment in a basin. The IR has been calculated as the ratio of the total reservoir storage capacity to the mean annual runoff. When the IR is > 1, the capacity of the reservoir is higher than the mean annual water yield of the basin. For example, the IR = 0.99 of the River Muga indicates that the reservoir regulates the 99% of the basin's runoff. Because the IR upstream the reservoir or before its construction is always 0, the index was calculated with the annual runoff downstream from the dam. When a gauging station was under the influence of more than one dam, the storage capacities of the dams were jointly considered.

To determine the changes in the magnitude and frequency of floods, we estimated the X-year return period (T_x) using the Gumbel law, as it is commonly used in magnitude and frequency analyses. Although total probability methods are the best option to analyse flood frequency (Durrans, 1988), when the principal use of the reservoirs is not flood prevention, the Gumbel method is also adequate because of the usual low regulation space (USACE, 1993). Estimations were performed using maximum annual daily flows (i.e. Q_c). Among them, Q_2, Q_{10} and Q_{25} (i.e. discharges with a recurrence interval of 2, 10 and 25 years, respectively) were selected to include lower flood magnitudes, which usually are the most affected by river regulation and the ones that define channel formation and sediment transport capacity. The Q_{25} could not be estimated for all the stations because some data series were not sufficiently long (i.e. River Orb). Finally, we calculated the δ parameter ($\delta = Q_{non\text{-}altered}/Q_{altered}$) to determine the impact of dams' construction on X-year return period.

The months with the highest and lowest flood decline were estimated by the comparison of the monthly maximum discharges. Thus, Q_c per month and year was selected, and the average of these Q_c values of the same months was calculated. The comparison was performed as follows: % $Q_{c\_monthly}$ changes = ($Q_{c\_monthly}$ post-dam - $Q_{c\_monthly}$ pre-dam) /$Q_{c\_monthly}$ pre-dam × 100.

Temporal analysis

Hydrological data were analysed at daily, monthly and annual temporal scales. Alterations at the daily scale were assessed by the flow standard deviation (hereafter FSD after Batalla et al., 2004), that uses the median and percentiles P_5, P_{16}, P_{84} and P_{95}. Monthly alteration was quantified statistically by the correlation coefficient between the non-altered and altered monthly flows (hereafter $\Phi_{pre,post}$). This variable corresponds to the division of the covariance between the two data sets by the product of their standard deviations and informs on the variation between the altered mean monthly flow distribution in relation to the non-altered flows. For instance, a $\Phi_{pre,post}$ near 1 indicates that the monthly pattern has not considerably changed, while a value of -1 would reflect a complete inversion of the flow regime. The coefficient does not give information about magnitudes in absolute values, i.e. one monthly regime can be half of the other but still may show a correlation coefficient near 1. The annual variation was assessed by the calculation of the percentage of runoff change between non-altered and altered conditions.

Indicators of hydrologic alteration

The IHA software (Richter et al., 1996) calculated selected parameters related to flow magnitude, frequency and duration, so the hydrological attributes of data series before and after dam construction could be quantified. The statistics calculated with the IHA method were non-parametric because the hydrological data do not follow a normal distribution, with exception of the up-ramp rate, where parametric statistics (i.e. mean and standard deviation) were used. Parameters were calculated in the frame of the EFC, and the criteria used in this paper to differentiate between categories were (i) extremely low flows: low discharges that correspond to less than 10% of the daily discharges, (ii) low flows: those representing below the 50% of the discharges, (iii) high flow pulses: flows that exceeded the 75% the daily flows, (iv) small floods: high flows greater than 2 years of return period and (v) large floods: flows greater than 10 years of return period. These parameters were later related to the duration and frequency of floods. Duration of discharge (in days) was quantified for extremely low flows, high flow pulses and small floods. Frequency of discharges was quantified only for the high flow pulses because of their significance for the channel river morphology. Finally, the mean up-ramp rate, which is defined as the increase of discharge per day (when it raised), was calculated as a measure of the river 'torrentiality' (e.g. this can also be interpreted as a proxy for the degree of the mediterraneity of a river and related to the rate of flow energy expenditure in the channel).

RESULTS

The Impounded Runoff index (IR, Table 3.2) ranged between 0.16 and 1.19 right downstream the dam. The highest values were found in the Siurana and Muga (1.19 and 0.99, respectively), whereas the lowest were estimated in the Têt and Cardener (0.16 and 0.19). IR decreased with the downstream increase in annual runoff and drainage area, except in the River Llobregat, where it increased (i) between stations EA067 to EA031 because annual runoff diminishes downstream and (ii) between EA023 and EA005, after the construction of la Baells Reservoir, which contributed to an increase of the IR index and a decrease of mean annual runoff (Figure 3.1).

Flow alteration at different temporal scales

Three zones of runoff generation were established using the non-altered mean annual runoff: (i) northern rivers (i.e. Orb and Aude), > 600 mm; (ii) southern basins (i.e. Foix and Siurana), < 200 mm and (iii) basins from the Agly to the Cardener, with runoff generation between 350 and 500 mm/year. Differences between zones were consistent downstream from the reservoirs and after the impact (Table 3.2).

Table 3.2. IR and changes in flows at three different temporal scales: annual, monthly and daily (see Figure 3.1 for location details).

		Dam	IR		Annual scale			Monthly	Daily scale	
					Mean annual runoff		Runoff		FSD	
			Non-altered	Altered	Non-altered	Altered	change (%)	$\Phi_{pre,post}$	Non-altered	Altered
Regulated										
ORB	Y2504010	Avene	0.00	-	650.82	-	3.7	0.83	11.74	-
	Y2504020		-	0.27	-	675.19			-	5.67
	Y2514020		-	*0.14*	-	*636.07*		*0.88*	-	*6.62*
	Y2554010		-	*0.05*	-	*831.76*		*0.88*	-	*8.32*
	Y2584010		-	*0.04*	-	*620.01*		*0.88*	-	*7.48*
AUDE	Y1112010[a]	Matemale + Puyvalador	0.00	0.22	665.56	637.22	-4.3	0.90	4.18	3.96
				0.08		581.79	-12.6	0.89		4.25
	Y1232010		-	*0.05*	-	*347.47*		*0.80*	-	*5.98*
	Y1612010		-	*0.02*	-	*270.99*		*0.64*	-	*7.27*
AGLY	Y0624020	Caramany	0.00	-	398.61	-	-36.94	0.81	10.15	-
	Y0634030		-	0.23	-	251.36			-	7.47
	Y0664040		-	*0.19*	-	*152.27*		*0.89*	-	*21.73*
TÊT	Y0424010	Vinçà	0.00	-	370.24	-	-9.24	0.85	3.88	-
	Y0464050		-	0.16	-	336.04			-	5.31
	Y0474040		-	*0.08*	-	*235.65*		*0.65*	-	*10.19*
MUGA	EA012	Darnius	0.00	0.99	386.65	323.36	-16.4	-0.79	9.49	8.69
	EA052		-	*0.59*	-	*138.70*		*55*	-	*15.18*
TER	EA019	Sau-Susqueda	0.00	-	311.63	-	-34.5	0.72	6.62	-
	EA010		-	0.87	-	204.11			-	8.25
CARDENER	EA025	Sant Ponç	0.00	-	406.89	-	-50.40	0.86	5.55	-
	EA001		-	0.19	-	201.83			-	5.19
	EA002		-	*0.12*	-	*154.72*		*0.86*	-	*4.98*

(continued on next page)

(Table 3.2 continued)

		Dam	IR		Annual scale			Monthly	Daily scale	
					Mean annual runoff		Runoff change (%)	$\Phi_{pre,post}$	FSD	
			Non-altered	Altered	Non-altered	Altered			Non-altered	Altered
Regulated										
LLOBREGAT	EA078	La Baells	0.00	-	493.75	-	-48.1	0.86	8.29	-
	EA066		-	0.57	-	360.09		0.75	-	4.12
	EA067		-	*0.46*	-	*232.42*		*0.78*	-	*4.30*
	EA031		-	*0.54*	-	*108.16*		*0.74*	-	*6.05*
	EA023[a]		*0.00*	*0.23*	*129.23*	*178.55*	*38.2*	*0.42*	*5.83*	*6.25*
		LaBaells +		*0.26*		*155.73*	*20.5*	*0.60*		*4.63*
	EA005[a]	*StPonç*	*0.00*	*0.17*	*112.90*	*168.97*	*49.7*	*0.38*	*5.69*	*7.65*
				0.27		*109.03*	*-3.4*	*0.54*		*6.49*
SIURANA	EA041+C4 042	Siurana	0.00	1.19	199.30	117.42	-41.8	-0.64	10.03	18.28
Non-regulated										
TECH	Y0254040	-	-	-	509.41	-		-	7.27	-
FLUVIÀ	EA016	-	-	-	245.07	-		-	5.31	-
FOIX	EA008	-	-	-	30.86	-		-	18.71	-

[a] Gauging stations with one pre-dam and two post-dam series.

Data in italics correspond to data series used to assess recovery downstream

The percentage of change in runoff between the mean annual runoff of altered sites and that of the non-altered ones indicates a general reduction in annual runoff, with the exception of the Orb (4% higher). Greater changes (> 30% reduction) after dam construction were observed in the southern basins (from the River Ter to the River Siurana) but also in the Agly. A notable reduction of specific annual runoff occurred downstream in all the studied basins, although the absolute mean annual runoff was higher. This fact could be related to the non-homogeneous runoff generation in the basins (i.e. higher runoff generation in the headwaters because of higher rainfall and a progressively decrease downstream the basin). Data series of non-regulated rivers (i.e. Fluvià and Foix, Figure 3.2) show a steady trend in annual runoff during the 20th century but also decreasing trend since the 1970s. These changes in runoff could not be directly associated with changes in total precipitation (*p*-values for the Mann-Kendall trend test analysis were > 0.05 in all cases), which indicated that rainfall did not show any trend. The average difference between the predicted WY and the observed pre-dam WY (1951-1969) was -0.02 mm, showing that the impact of the precipitation was negligible. However, the differences of predicted WY and observed post-dam WY were 215 mm, which can be interpreted as a notable impact of other factors, such as changes in land use. The land cover change for the whole region (Table S3.1, Supporting Information) confirms that urban area increased (88% with respect the 1990 but less than 1 km^2 in absolute terms), and forest surface increased too (mean increase of 3.3%). This comparison also shows substantial differences between basins: while changes were between -0.2% and 0.2% in the Orb, Muga, Fluvià and Ter, in the Aude, Têt, Tech and Llobregat increase ranged between the 3% and 6% and reached 18% in the River Foix. Changes in agricultural land were not important (mean decrease of 1.7%), and changes in grasslands and scrublands were more visible in the French basins than in the Spanish ones (9.3% and 1.9% reduction, respectively).

The studied rivers could be arranged in two groups regarding the alteration of monthly flows ($\Phi_{pre,post}$, Table 3.2). The Muga and Siurana showed a negative $\Phi_{pre,post}$, with values of -0.79 and -0.65, respectively, while all the others have values > 0.7. Values > 0.7 indicate that the alteration of the monthly regime is relatively low and that the post-dam distribution is similar to the non-altered one. $\Phi_{pre,post}$ between mean monthly flows recovered downstream in the Orb, Agly and Muga, but it remains altered in the Aude, Têt, Cardener and Llobregat. The Muga recovered the most to the non-altered seasonal flow distribution ($\Phi_{pre,post}$ from -0.79 to 0.55), while the Llobregat was the one experiencing a more sustained change in its monthly regime downstream ($\Phi_{pre,post}$ from 0.75 in EA078 to 0.54 in EA005, see Figure 3.1 for location details). A rather scattered pattern was observed when plotting the IR index versus $\Phi_{pre,post}$ (Figure 3.3a), with a visual breaking point appearing to exist between $0.6 < IR < 0.9$. As indicated, the Muga and Siurana were the two rivers with a $\Phi_{pre,post} < 0$ and also are those with a higher IR index.

Flow standard deviation in natural conditions varied between 3.9 and 12, and immediately after the dam construction values ranged from 4 to 18 (Table 3.2). Those rivers with lower specific discharges were the most variable (e.g. FSD > 10, Agly, Muga, Siurana and Foix). Low flows (P_5) generally increased after dam construction (Table S3.2, Supporting Information), with the exception of the Aude and Muga (this one having half of the pre-dam discharge, from 0.35 to 0.16 m^3/s). Conversely, the River Llobregat tripled its low flows (from 0.9 to 2.9 m^3/s). Median discharges tend to increase in six of the rivers. In the Aude and Ter, median discharges remained equal after dam construction, while in the Siurana were substantially reduced (from 0.25 to 0.12). High discharges (P_{95}), also rose in six cases and were reduced in three; the Aude, Muga and Siurana slightly diminished their high flows. When moving downstream, FSD recovered most of its natural variability, except in the Cardener. Overall, FSD is, in the majority of rivers, higher at the outlet than at the headwaters.

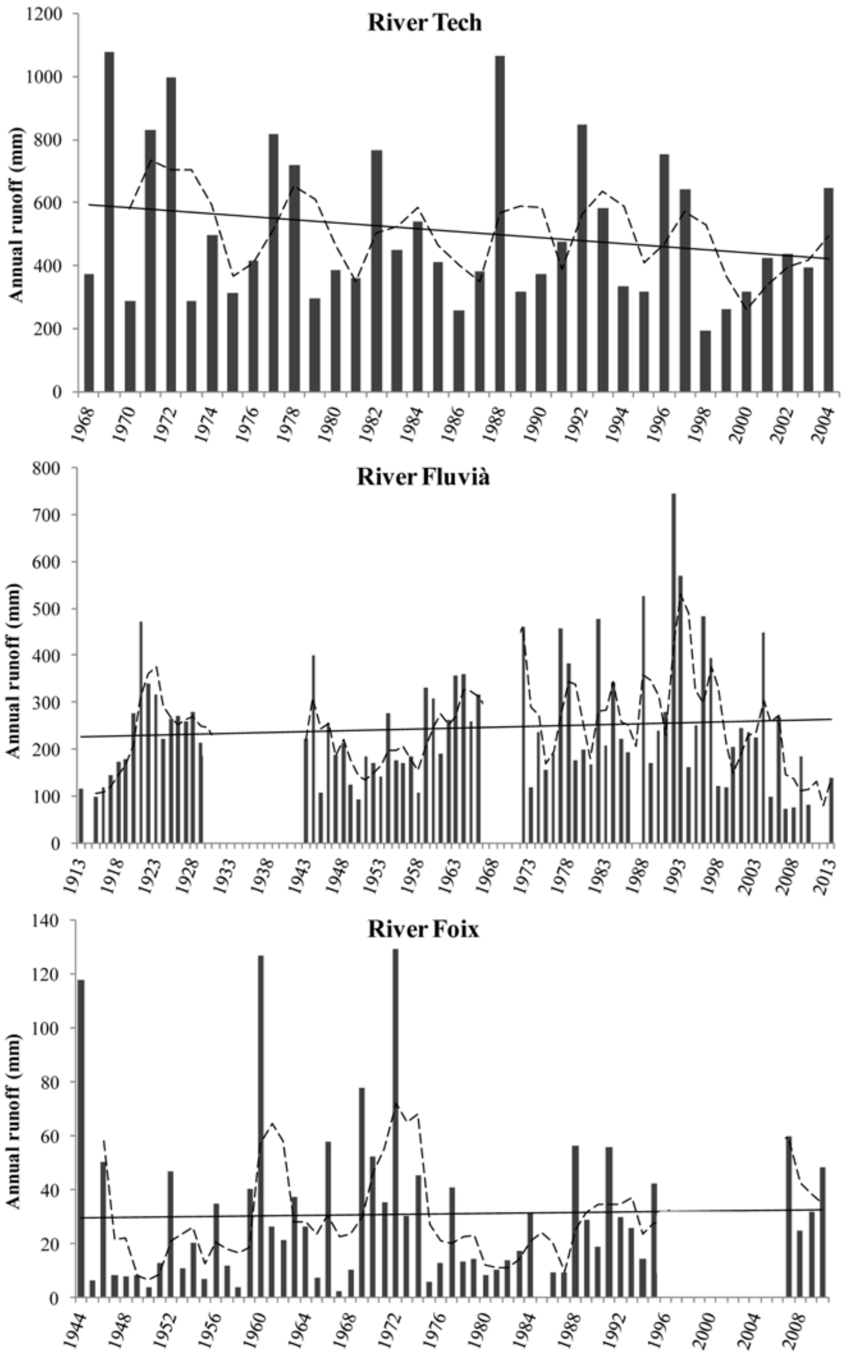


Figure 3.2. Annual runoff in non-regulated rivers. Linear trends (simple line) and moving average (3 years, dotted line) are also represented.

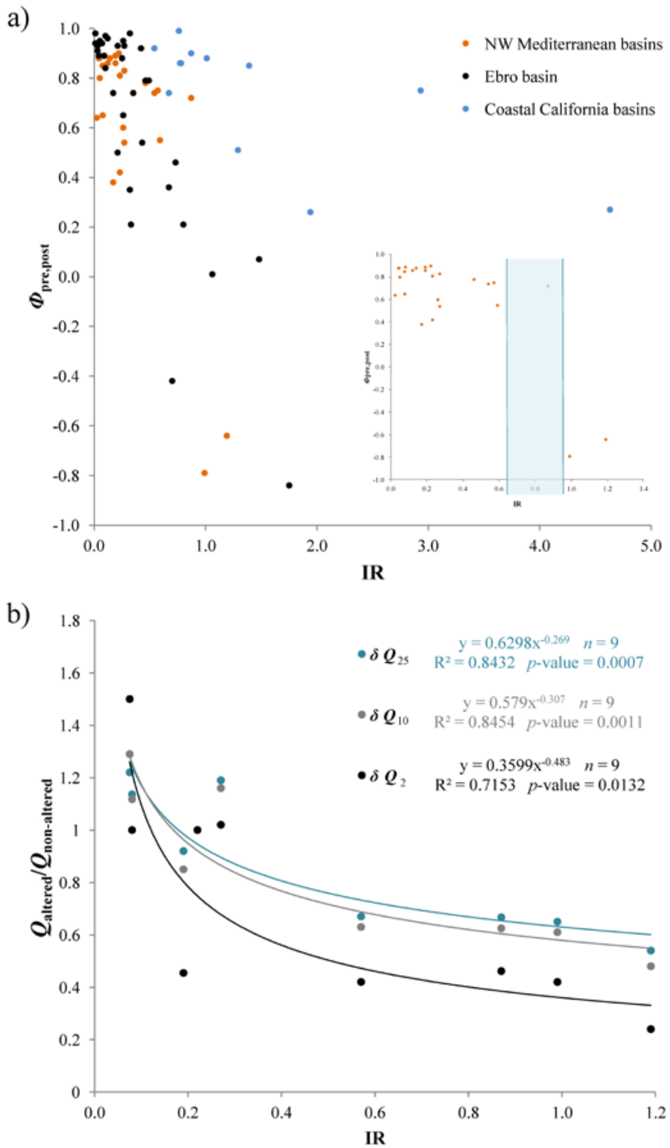


Figure 3.3. a) Changes in mean monthly flows related to IR index. The graph includes altered points immediately downstream the reservoir and points km downstream. The same analysis was performed for the Ebro river (Batalla et al., 2004) and for the Sacramento-San Joaquin basins (Kondolf and Batalla, 2005), and points have been added allowing comparison with other Mediterranean cases. The inset shows the break between 0.6 > IR > 1 for Mediterranean basins (except for the River Ter, where two continuous reservoirs considered together enlarge the IR ratio); b) Flow magnitude reduction after dam construction as a function of IR. Study points located only immediately downstream the reservoir were included for this analysis.

Alteration of magnitude, frequency and duration of floods

Flood reduction after dam construction was general (Table 3.3 and Table S3.3 of Supporting Information). Mean reduction for the Q_2, Q_{10} and Q_{25} was 54%, 34% and 30%, respectively. The Agly was the less altered river (δ Q_2 = -38%, δ Q_{10} = -25 and δ Q_{25} = -23%), whereas the Siurana showed the highest alteration (δ Q_2 = -76%, δ Q_{10} = -52 and δ Q_{25} = -46%). Although magnitude of Q_2 does not decrease in all rivers, frequency diminishes (frequency of high flow pulses in Table 3.4 and Table S3.4 of Supporting Information). This reduction is maintained downstream, so there is no recovery of the frequency of these discharges near the outlet. Figure 3.3b shows the relation between IR and $Q_{altered}/Q_{non\text{-}altered}$ for different return intervals. In general, the more altered are floods as IR increases, with higher reductions in its magnitude and frequency. A higher dispersion is observed when IR < 0.3, although maybe this fact could be related to the limited number of points considered. At the same time, only rivers with low IR (< 0.3) have $\delta > 1$ ($Q_{non\text{-}altered} < Q_{altered}$). Greater reductions occur when T_x is lower (δ Q_2 > δ Q_{10} > δ Q_{25}), with the exception of the rivers Orb, Aude and Têt (Table 3.3), which are inversed. The rivers Orb and Aude separated

Table 3.3. Changes in the 2-, 10- and 25-year return periods after the dams construction.

		Q_2 ($m^3/s\cdot km^2$)	Q_{10} ($m^3/s\cdot km^2$)	Q_{25} ($m^3/s\cdot km^2$)
ORB	Y2504010-Y2504020	1.02	1.16	-
AUDE	Y1112010[a]	1.00	1.00	1.00
		1.00	1.12	1.14
AGLY	Y0624020-Y0634030	0.62	0.75	0.77
TÊT	Y0424010-Y0464050	1.50	1.29	1.22
MUGA	EA012[b]	0.42	0.61	0.65
TER	EA019-EA010	0.46	0.63	0.67
CARDENER	EA025-EA001	0.45	0.85	0.92
LLOBREGAT	EA078-EA066	0.42	0.63	0.67
	EA023[a]	1.50	1.83	1.75
		0.88	2.10	2.15
	EA005[a]	1.50	1.71	1.88
		0.78	1.43	1.88
SIURANA	EA041+C4042[b]	0.24	0.48	0.54

[a] Gauging stations with a pre-dam and two post-dam series.
[b] Gauging stations with pre-dam and post-dam data.

from the described patterns and showed almost no change. Further, the Têt increased their flood magnitude after damming: Q_2 increased 50% downstream from the dam, and Q_{10} and Q_{25} increased 29% and 22%, respectively. Both the management of the dam and the entrance of tributaries downstream the dam could justify these values, which also coincide with low IR values (i.e. < 0.16), an indication of the little control on basin's runoff exerted by the dam.

Months with the highest flood decline (i.e. higher Q_{max} reduction) after dam construction were generally the autumn months (October and November; Table 3.5 and Table S3.5 of Supporting Information). This monthly reduction was especially visible in the River Muga (Q_{max} reduction was of the 90% after the impact in both months) and in the River Siurana (Q_{max} in October was 80% lesser after the dam construction). The months with the lowest flood decline were highly dependent on the river. The lower reductions in winter months were observed in the Aude and Llobregat (decreases lower than 10% and 17% respectively in January and February). In general, the most affected rivers were the Muga, the Cardener and the Siurana, despite having some months with higher maximum monthly flows after the dam construction (i.e. January in the Muga and July in the Siurana).

Common patterns for all the basins could not be established regarding the duration of extremely low flows, high flow pulses and small floods (Table 3.4 and Table S3.4 of Supporting Information). Nevertheless, a general recovery of high flow pulses existed downstream. Small floods also recovered (except for the River Cardener), and similar values to the non-altered ones were observed near the outlet of the basins.

Table 3.4. Changes in the mean daily flow, median duration and frequency of flows and mean up-ramp rate after dam construction.

		% change mean daily flow	**% change duration extremely low flows**	**% change duration high flow pulses**	**% change duration small floods**	**% change frequency high flow pulses**	**% change mean up-ramp rate**
ORB	Y2504010	-	-	-	-	-	-
	Y2504020	3.88	-38.46	-42.11	-54.55	-29.41	-26.18
	Y2514020	*-1.94*	*-46.15*	*-15.79*	*-26.14*	*-17.65*	*67.43*
	Y2554010	*28.16*	*-38.46*	*-47.37*	*-1.14*	*5.88*	*420.31*
	Y2584010	*-4.85*	*-42.31*	*-36.84*	*0.00*	*-23.53*	*594.24*
AUDE	Y1112010	-5.21	11.11	-33.33	-54.55	-29.41	4.30
		-14.69	-55.56	-33.33	-20.45	-11.76	-33.71
	Y1232010	*-47.87*	*-55.56*	*-33.33*	*-17.05*	*-17.65*	*68.05*
	Y1612010	*-59.24*	*-33.33*	*0.00*	*-7.95*	*-29.41*	*410.16*
AGLY	Y0624020	-	-	-	-	-	-
	Y0634030	-36.51	350.00	128.57	184.09	-60.00	-11.39
	Y0664040	*-61.90*	*137.50*	*28.57*	*175.76*	*-40.00*	*246.34*
TÊT	Y0424010	-	-	-	-	-	-
	Y0464050	-9.40	100.00	75.00	-69.05	-6.25	153.37
	Y0474040	*-35.90*	*100.00*	*50.00*	*-58.10*	*-25.00*	*356.36*
MUGA	EA012	-17.07	-66.67	-15.00	-54.10	-25.00	-75.90
	EA052	*-64.23*	*55.56*	*-20.00*	*0.82*	*-41.67*	*96.17*
TER	EA019	-	-	-	-	-	-
	EA010	-34.34	275.00	0.00	41.51	-36.36	-39.44
CARDENER	EA025	-	-	-	-	-	-
	EA001	-50.77	-40.00	0.00	24.07	-18.75	19.91
	EA002	*-62.31*	*-60.00*	*-25.00*	*-9.26*	*-18.75*	*77.09*
LLOBREGAT	EA078	-	-	-	-	-	-
	EA066	-9.62	-33.33	15.00	-30.00	-33.33	17.66
	EA067	*-52.56*	*-22.22*	*-60.00*	*8.00*	*16.67*	*-11.95*
	EA031	*-164.41*	*-125.00*	*-66.67*	*40.48*	*25.00*	*34.50*
	EA023	*39.02*	*-76.47*	*81.82*	*70.00*	*-40.00*	*37.85*
		17.07	*-64.71*	*18.18*	*80.00*	*-50.00*	*-39.74*
	EA005	*47.22*	*-42.86*	*-10.00*	*11.11*	*-10.00*	*508.29*
		-5.56	*-42.86*	*-80.00*	*11.11*	*-10.00*	*191.57*
SIURANA	EA041+C4042	-41.10	83.33	-21.43	-71.86	0.00	-32.25

Data in italics correspond to data series used to assess recovery downstream.

Table 3.5. Changes between the pre-dam and post-dam monthly maximum flows for the regulated Mediterranean studied rivers. Data is presented in % and is only shown for the difference between altered and non-altered sites. The recovery downstream can be checked in the *Supporting information*.

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Orb	-54.7	-70.4	-72.7	-39.5	-51.6	-32.8	-36.5	7.1	-35.7	146.1	206.2	13.7
Aude1	-32.1	-32.5	-19.4	-4.4	-10.4	-10.4	19.1	6.8	-9.5	-24.0	25.9	70.9
Aude2	-51.2	-24.0	-0.8	2.1	-33.2	2.0	4.9	-3.8	-24.1	-34.4	-9.6	38.0
Agly	-56.7	-80.5	-37.4	-52.4	-44.8	-30.4	-36.6	-36.6	-46.0	-16.1	4.5	-38.4
Têt	31.8	7.9	55.8	104.1	22.4	2.1	24.9	19.3	-7.2	-24.6	-21.3	-14.1
Muga	-90.1	-90.7	-21.1	94.3	-50.5	-62.4	-35.0	-12.9	13.5	73.4	24.7	-79.6
Cardener	-62.8	-41.9	-46.9	-53.2	-55.8	-49.6	-56.0	-49.5	-63.4	-60.5	-62.4	-57.2
Llobregat	-70.3	-15.9	-67.3	-17.2	-14.8	-49.0	-42.8	-45.9	-41.4	-20.8	-42.5	-57.5
Siurana	-84.1	-60.3	-28.1	-48.5	-47.1	-82.8	-75.5	-67.0	-29.8	98.7	59.3	-68.9

Aude1 corresponds to the change after the construction of the Puyvalador reservoir; Aude2 corresponds to the change after Matemale resevoir.

Alteration of torrentiality

Mean up-ramp rate (Table 3.4 and Table S3.4 of Supporting Information) was used as a measure of torrentiality of the river; the larger the increment of discharge per day, the more torrential a river can be considered. A general decrease of the up-ramp rate occurs in the altered sites, except in the rivers Têt and Llobregat, which showed a mean increment in the daily rates from 0.73 to 1.86 m^3/day, and from 1.94 to 2.29 m^3/day, respectively. The Cardener showed a steady mean up-ramp rate though a high dispersion coefficient. Greater reductions occurred in the rivers Muga and Ter, where mean up-ramp rates decreased more than 2 m^3/day. In general, a recovery (i.e. increase) of up-ramp rates occurred downstream from the altered sites; in some cases (e.g. Orb and Aude), the outlet values were higher than the non-altered rates, whereas in others (e.g. Llobregat), rates at the outlet were similar to the non-altered sites. In the particular case of the River Muga (Figure 3.4), a notable change existed between the non-altered and altered sites. Although the coefficient of variation was similar in both cases (calculated with daily data), the mean up-ramp rates were more variable between years in the non-altered, and the inter-annual variability diminished considerably after dam construction.

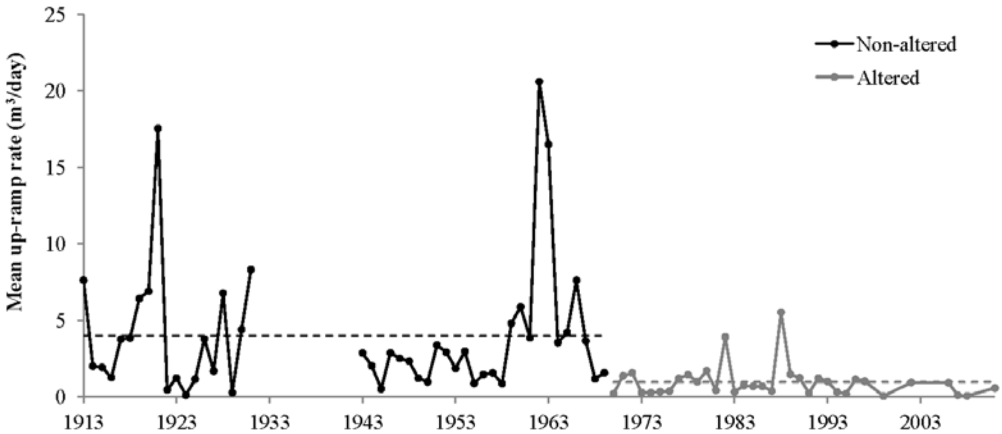


Figure 3.4. Mean up-ramp rate for the River Muga before and after dam construction

DISCUSSION

Dams' impact on hydrology

The decrease of annual runoff downstream from dams was a general trend in all the studied basins. Water withdrawals are the principal human cause for the long-term decrease of annual runoff at a global scale (Döll et al., 2009). Mediterranean regions have high water consumption, so the decrease of average annual discharge can be not only affected by losses of water storage in reservoirs and its release for water demands but also by the effects of diversions and by-passes. These high pressures diminish runoff in water-scarce regions in a way that makes it improbable to return to previous discharges (Milliman et al., 2008). Other factors such as water evaporation from reservoirs may be also important, but the runoff reduction in our studied set of cases did not follow a latitudinal gradient probably because of the short north-south distribution of the basins. Precipitation accounted for runoff generation in a given basin but was not the only factor to consider for the hydrological river response. Different hydrological responses to the same input may respond to specific water uses and/or to dam operation. The reduction of discharge observed in non-regulated rivers can be related to land use changes (some increase in urban areas, reduction of agriculture and afforestation have been observed in the area) as it has been indicated previously (e.g. Gallart and Llorens, 2002; López-Moreno et al., 2006; Buendia et al., 2015).

The volume of water stored in the reservoirs before and during floods also affects the peak discharge downstream from the dam. In our study area, flood seasons are usually preceded by lower flows (i.e. summer and winter) upstream the reservoirs, so sufficient storage space is available before the major rainfall events of the year. Nevertheless, in case there is a second large flood in a short period of time, some space should be allocated (Harmancioğlu, 1994). In those situations, real-time forecasting can be very helpful for reservoirs management, giving the manager better capacity and criteria to respond to the incoming flood, hence reducing flooding risk downstream (e.g. Votruba and Broža, 1989; Connaughton et al., 2014).

The IR-$\Phi_{pre,post}$ relations (Figure 3.3a) suggest the existence of a trend between altered and non-altered mean monthly flows, although results become more scattered as IR increases. The NW Mediterranean basins used in this paper have analogous scatter as that observed in the Ebro sub-basins (Batalla et al., 2004). Coastal California basins (Kondolf and Batalla, 2005) also follow a similar trend but show stronger impacts, i.e. similar IR results in $\Phi_{pre,post}$ close to 1, and higher IR has greater changes on flow regimes. This can be related to different natural hydrological regimes (i.e. one peak in winter or moved to spring in Californian basins, two peaks in spring and autumn in the Mediterranean basins and more than one in the Ebro sub-basins). A scale effect can also exist because of higher runoff generation and to the larger reservoir capacity in Californian than in the Mediterranean basin rivers' systems. Daily variability reduces after the dam presence, because the large flows tend to be smoothed. The observed fact that low flows are higher downstream a dam has been also widely reported (Batalla et al., 2004; Magilligan and Nislow, 2005; Döll et al., 2009). Floods are also affected in their frequency and magnitude (e.g. Abam, 1999; Fitzhugh and Vogel, 2011). The absence of relationships between daily variability and dams' uses can be related to the multiple purposes that the reservoirs are used for. For instance, Magilligan and Nislow (2005) found that greater modifications in post-dam monthly flows occur in US dams that have hydropower generation as the main function.

The fact that most altered flows are the ones with lower return interval has been reported elsewhere (e.g. Kondolf and Mathews, 1991; Batalla et al., 2004). Nevertheless, the Orb, Aude and Têt increased its magnitude and frequency of floods downstream. In the Têt and Orb, this particular pattern might respond to the entrance of unregulated tributaries between upstream and downstream stations.

River dynamics downstream from dams

Natural variability of mean monthly flows sustains habitat suitability for aquatic ecosystems and water for terrestrial organisms and plants, and controls water temperature, oxygen levels and photosynthesis (The Nature Conservancy, 2009). Thus, modifications in the flow regime may induce changes not only in the aquatic ecosystems but also in the terrestrial others. Conversely, the maintenance and recovery of the daily flow variability observed downstream of reservoirs and at the river's mouth guarantees the sustainability of freshwater ecosystems (Baron et al., 2002). Nevertheless, it is difficult to describe the necessary range of flows to define an ecosystem as healthy (Mathews and Richter, 2007). The reduction of magnitude and frequency of extreme events as floods or high flow pulses that have been assessed in six of the nine regulated rivers reduces the connectivity between rivers and floodplains and produces biodiversity losses (e.g. Goodwin et al., 2006). These events are capable to transport high quantities of sediments and are highly affected after dam construction because reservoirs trap particulate matter, and released water has less energy to transport material (Kondolf, 1997); this has effects on the channel morphology (e.g. Vericat and Batalla, 2005; Gordon and Meentemeyer, 2006). Although floods are the events determining channel form, high flow pulses also have geomorphic effects as erosion of channel banks and channel sediment texture (e.g. Graf, 2006; Vericat et al., 2006). Duration and frequency of these events, mainly reduced after dam construction, determine the stress conditions related to soil moisture that plants have to face, as low oxygen availability (The Nature Conservancy, 2009). Reduction of large autumn floods may affect riverbed regeneration. Other extreme events, as the extremely low flows, have also impacts on riparian vegetation depending on their recurrence and duration. Even though no clear patterns were observed in our study rivers, other Iberian rivers (i.e. Tagus) increased the magnitude of droughts downstream the reservoir (López- Moreno et al., 2009). The lack of patterns regarding low flows may be related to the different reservoir management of each basin. The rate of increase of daily flow (up-ramp rate) has been taken as a measure of torrentiality. The observed reduction after dam construction determines less erosion in banks and bars (Graf, 2006) and, at the same time, favours vegetation encroachment in formerly active areas (Batalla et al., 2006) and diminishes the possibility of organisms entrapment in island or floodplains because of rapid inundation (The Nature Conservancy, 2009).

Downstream recovery

The hydrological complexity of Mediterranean basins difficults the understanding of the factors related to the downstream recovery from dam impacts. We have used two basins (Muga and Cardener-Llobregat) as examples of causes determining such differences.

Dam construction in the River Muga caused an inversion of the mean monthly flows few kilometres downstream the dam, although the hydrological regime recovered near the river mouth (Figure 3.5). This alteration is also expressed on the flood magnitude and frequency, i.e. occurring a great reduction immediately downstream the dam but recovering at the mouth. Water demands for irrigation and urban uses (e.g. tourism) during summer months, when less runoff naturally occurs, caused an inversion of the hydrological regime. The monthly evolution of the water stored in the Darnius Boadella Reservoir (Figure 3.6) shows an evident inversion of its hydrological regime after dam construction. This dam is progressive infilled from October to June (when it reaches the highest volume) and rapidly emptied during the summer months (July, August and

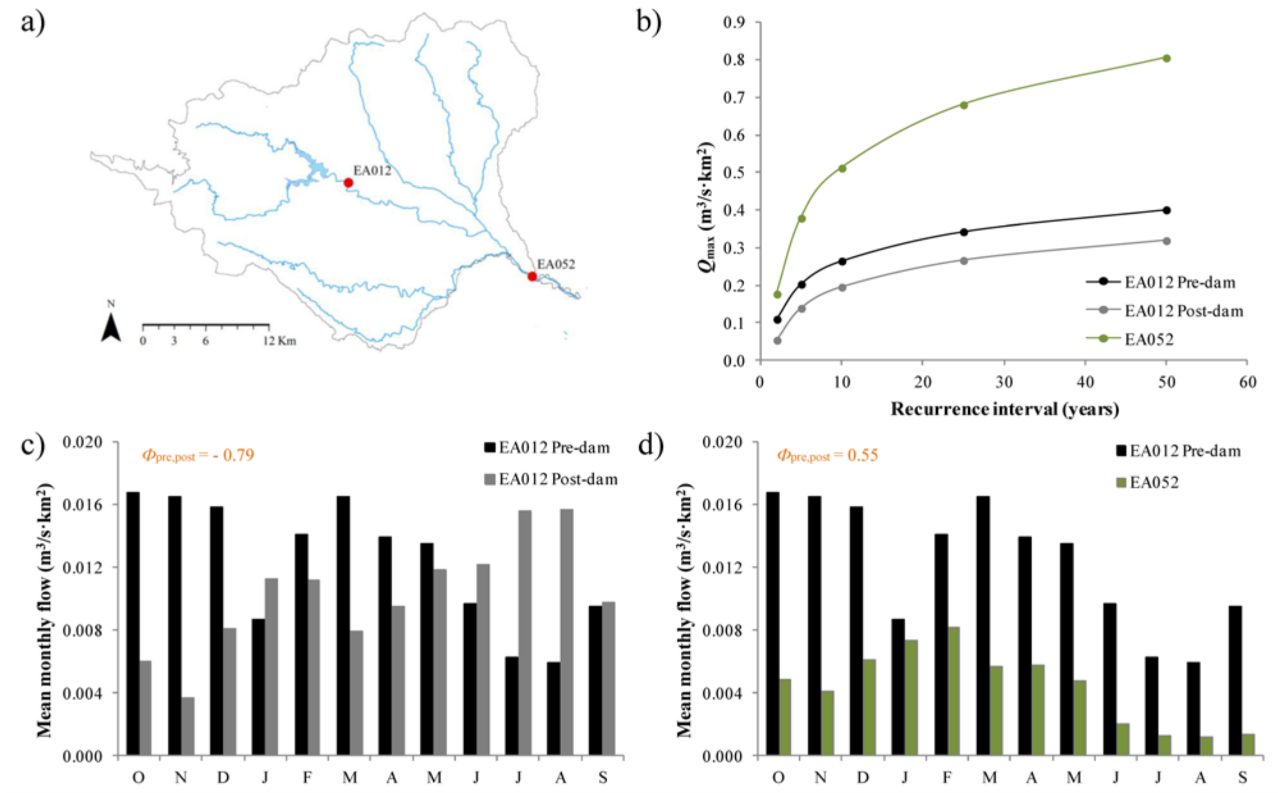


Figure 3.5. Downstream recovery for the River Muga. a) Muga basin with location of gauging stations analysed and principal tributaries; b) Flood frequency analysis; c) Comparison of mean monthly flows before and after dam construction; d) Comparison of pre-dam and outlet mean monthly flows.

September). Late summer is the moment with less water stored during the year. Inflow regime is quite different (in shape) to the outflow regime, which can be related to the high alteration of the mean monthly flows ($\Phi_{pre,post}$ = -0.79). The non-regulated tributaries, which drain almost half of the basin and maintain a natural flow regime, contribute to the recovery at the outlet both for the flow regime and the magnitude and frequency of floods.

The River Llobregat is strongly affected by withdrawals and water diversions (e.g. Marcé et al., 2012). Despite this, upstream the confluence of the Cardener and Llobregat (Figure 3.7a and b) the seasonal flow regime after reservoirs construction did not change, although mean monthly flows diminished substantially. Regarding flood magnitude and frequency, there was a reduction from upstream to downstream. The monthly water storage of la Llosa del Cavall and la Baells reservoirs (Figure 3.6) is linked to the non-altered mean monthly flows of both rivers. Hence, these reservoirs are infilled from October to December, when they remain more or less stable until March because of low flows coming from upstream. From April to June, spring rain events and probably snowmelt increase the water that can be stored in the reservoir and, finally, the water demands during summer months (i.e. July-September) make the water storage volume to reduce considerably. The Sant Ponç Reservoir has a similar pattern, but it is influenced by the upstream la Llosa del Cavall Dam. Inflow and outflow regimes are similar regarding its distribution along the year; it coincides with variations in monthly flow regimes, which were close to 1. Downstream the confluence (Figure 3.7c and d), flow regime changed after Sant Ponç construction, but la Baells Dam aid to its recovery. Flow magnitude and frequency were reduced, but post-dam recurrence intervals are higher than pre-dam ones probably because of the diversion of water for urban uses. These operations also have an effect on annual runoff calculated at gauging stations and may result in an erroneous allocation of increments or reductions of runoff in relation to dam construction and operation. The combination of the two rivers (Cardener and Llobregat) evidences that, currently, human impact on river discharges is not only caused by dams but also by withdrawals and diversions to guarantee water supply. It is probably the cause for the propagation of flood alteration even kilometres downstream.

The Muga and Cardener–Llobregat systems exemplify how Mediterranean rivers studied in this paper show contrasting behaviours, where in some instances, flow parameters recover with distance from the dam, but others remain altered (especially in Llobregat but also Orb). They may respond to water supply for consumptive uses, which can also modify considerably seasonal flow regimes and may show stronger effects than reservoirs (e.g. Döll et al., 2009). These basins also evidenced that the impact of dam construction is noticeable kilometres downstream, similar to the observations elsewhere (e.g. Pyron and Neumann, 2008). According to Singer (2007), the distance travelled downstream of the reservoir and the confluence of tributaries allow the water flow recovery, but river flows may remain altered at different temporal scales and may extend down to the river mouth. The analysis of the recovery downstream (taking the Muga and Llobregat as examples) has shown that, in rivers where the anthropic effect is important, as it is in the Mediterranean, there is no pattern of recovery for the whole region. The recovery is neither related to other physical factors of the basin as size or IR (Muga recovers more in the outlet than the Llobregat, but it is smaller and has an IR index close to 1) but to the human impact again.

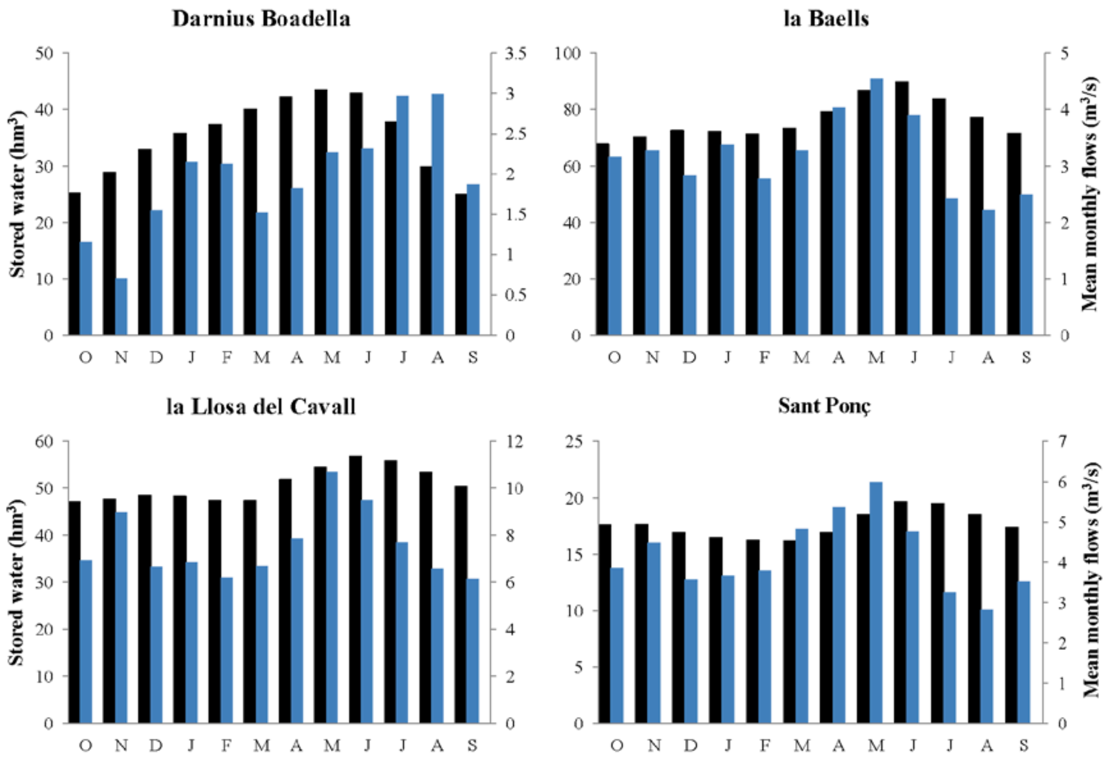


Figure 3.6. Reservoir inflow and outflow monthly regime for the reservoirs located in the Muga basin (i.e. Darnius Boadella reservoir) and in the Llobregat basin (i.e. la Baells, la Llosa del Cavall and Sant Ponç reservoirs). Black bars correspond to the stored water in reservoirs and blue bars correspond to the mean monthly flows of the nearest gauging station downstream the dam.

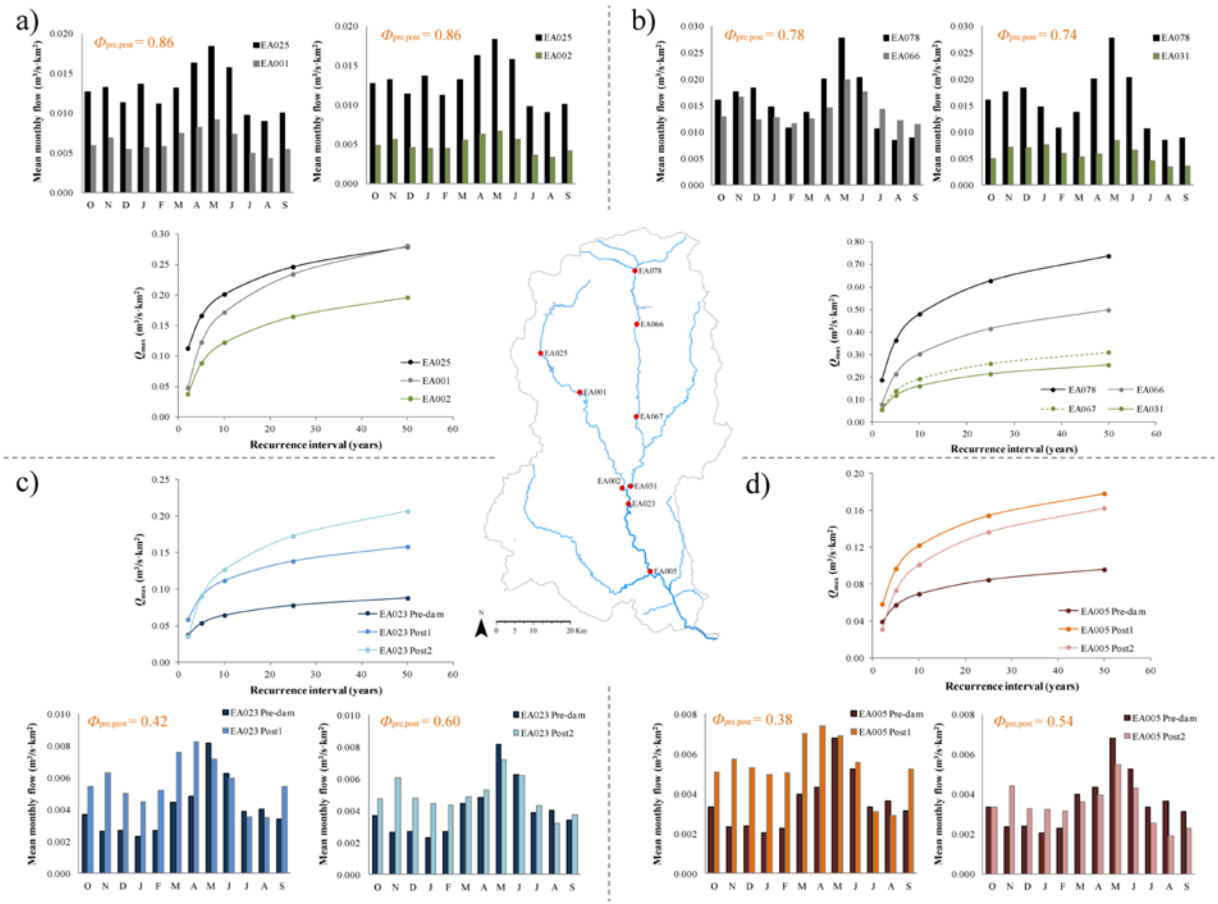


Figure 3.7. Downstream recovery for the Cardener and Llobregat rivers. Comparison between mean monthly flows and flood frequency analysis is shown for: a) Cardener sub-basin, b) Llobregat sub-basin, c) Gauging station EA023, where two post-dam periods are defined, d) Gauging station EA005, where two post-dam periods are defined.

CONCLUSIONS

Mediterranean rivers show minimum discharges in summer, coincident with higher water demand. Dams approach this problem by storing large quantities of water but impacts on hydrology persist kilometres downstream. It is concluded from our study that (i) dams in rivers of the western Mediterranean region generate a heterogeneous impact on the river flow at different temporal scales, (ii) monthly regimes and magnitude and frequency of flood events are overall affected by the presence of the dams, with likely consequences for river's geomorphology and ecology, and (iii) the downstream effects of dams are maintained tens of kilometres downstream and, in some cases, effects persist down to the river mouth. Inputs of tributaries have a recovery effect but rarely produce a complete recovery downstream.

Our results indicate that regulated basins in the NW Mediterranean region are affected by dam construction and operation but also show that the basins are affected to a different degree, thus precluding simple regional generalizations of the observed changes. Water availability is affected by the upstream climate and land uses in each basin, while downstream water demand and uses are the major determinants of water releases from reservoirs. Water demand for human consumption, irrigation and industrial uses is not only derived from impoundments but also through water diversions and withdrawals from other parts of the river. Moreover, other factors also influence river's hydrology by reducing annual basin's runoff, especially changes in land use. Future studies on Mediterranean river basins should consider dam impacts together with other disturbances derived from water demand, in order to reach a more comprehensive discrimination of the individual effects of impacts of river's flow regime.

SUPPORTING INFORMATION

Additional supporting information may be found at the end of this chapter.

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REFERENCES

Abam, T.K.S. (1999). Impact of dams on the hydrology of the Niger Delta. *Bulletin of Engineering Geology and the Environment*, 57 (3): 239-251.

Aristi, I., Arroita, M., Larrañaga, A., Ponsatí, L., Sabater, S., von Schiller, D., Elosegui, A., Acuña, V. (2014). Flow regulation by dams affects ecosystem metabolism in Mediterranean rivers. *Freshwater Biology*, 59: 1816-1829.

Barceló, D., Sabater, S. (2010). Water quality and assessment under scarcity: prospects and challenges in Mediterranean watersheds. *Journal of Hydrology*, 383: 1-4.

Baron, J.S., Poff, N.L., Angermeier, P.L., Dahm, C.N., Gleick, P.H., Hairston, N.G., Jackson, R.B., Johnston, C.A., Richter, B.D., Steinman, A.D. (2002). Meeting ecological and societal needs for freshwater. *Ecological Applications*, 12 (5): 1247-1260.

Batalla, R.J., Gómez, C.M., Kondolf, G.M. (2004). Reservoir-induced hydrological changes in the Ebro River basin (NE Spain). *Journal of Hydrology*, 290: 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*, 143: 1-15.

Beaumont P. 1978. Man's impact on river systems: a world-wide view. *Area*, 10: 38–41.

Beaumont, P. (1993). *Drylands: Environmental Management and Development*. Routledge: London; 560 pp.

Belmar, O., Velasco, J., Martínez-Capel, F., Marín, A.A. (2010). Natural flow regime, degree of alteration and environmental flows in the Mula stream (Segura River basin, SE Spain). *Limnetica*, 29 (2): 353-368.

Buendia, C., Batalla, R.J., Sabater, S., Palau, A., Marcé, R. (2015). Runoff trends driven by climate and afforestation in a Pyrenean basin. *Land Degradation and Development*, 27 (3): 823-838.

Connaughton, J., King, N., Dong, L., Ji, P., Lund, J. (2014). Comparing simple flood reservoir operation rules. *Water*, 6: 2717-2731.

Cooper, S.D., Lake, P.S., Sabater, S., Melack, J., Sabo, J.L. (2013). The effects of land use changes on streams and rivers in Mediterranean climates. *Hydrobiologia*, 719: 383-425.

Döll, P., Fiedler, K., Zhang, J. (2009). Global-scale analysis of river flow alterations due to water withdrawals and reservoirs. *Hydrology and Earth System Sciences Discussions*, 6 (4): 4773-4812.

Durrans, S.R. (1988). Total probability methods for problems in flood frequency estimation. In: Parent, E., Hubert, P., Bobee, B., Miquel, J. (eds): *Statistical and Bayesian Methods in Hydrological Sciences, Technical Documents in Hydrology*, vol. 20, UNESCO: Paris; 299-326.

Fitzhugh, T.W., Vogel, R.M. (2011). The impact of dams on flood flows in the United States. *River Research and Applications*, 27: 1192-1215.

Gallart, F., Llorens, P. (2002). Water resources and environmental change in Spain. A key issue for sustainable integrated catchment management. In: García-Ruiz, J.M., Jones, J.A.A., Arnáez, J. (eds): *Environmental Change and Water Sustainability*. Consejo Superior de Investigaciones Científicas: Zaragoza; 11-20.

Goodwin, P., Jorde, K., Meier, C., Parra, O. (2006). Minimizing environmental impacts of hydropower development: transferring lessons from past projects to a proposed strategy for Chile. *Journal of Hydroinformatics*, 8 (4): 253-270.

Goossens, C. (1985). Principal component analysis of Mediterranean rainfall. *Journal of Climatology*, 5 (4): 379-388.

Gordon, E., Meentemeyer, R.K. (2006). Effects of dam operation and land use on stream channel morphology and riparian vegetation. *Geomorphology*, 82 (3-4): 412-429.

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

Harmancioğlu, N.B. (1994). Flood control by reservoirs. In: Rossi, G., Harmancioğlu, N.B., Yevjevich, V. (eds): *Coping with Floods*. NATO ASI Series, Kluwer Academic Publishers: Dordrecht, 637-652.

Herrera, S., Gutiérrez, J.M., Ancell, R., Pons, M.R., Frías, M.D., Fernández, J. (2010). Development and analysis of a 50 year high-resolution daily gridded precipitation dataset over Spain (Spain02). *International Journal of Climatology*, 32: 74-85.

Kendall, M.G. (1975). *Rank Correlation Measures*. Charles Griffin: London; 202 pp.

Kondolf, G.M., Mathews, W.V.G. (1991). *Management of Coarse Sediment in Regulated Rivers of California*. Technical Completion Report W-748. University of California, Water Resources Center: Riverside. Davis.

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

Kondolf, G.M., Batalla, R.J. (2005). Hydrological effects of dams and water diversions on rivers of Mediterranean-climate regions: examples from California. In: Garcia, C., Batalla, R.J. (eds): *Catchment Dynamics and River Processes: Mediterranean and Other Climate Regions*. Elsevier: Amsterdam; 197-211.

López-Moreno, J.I., Begueria, S., García-Ruiz, R.M. (2006). Trends in high flows in the central Spanish Pyrenees: response to climatic factors or to and-use change? *Hydrological Sciences Journal*, 51: 1039-1050.

López-Moreno, J.I., Vicente-Serrano, S.M., Beguería, S., García-Ruiz, J.M., Portela, M.M., Almeida, A.B. (2009). Dam effects on droughts magnitude and duration in a transboundary basin: the Lower River Tagus, Spain and Portugal. *Water Resources Research*, 45: W02405.

Magilligan, F.J., Nislow, K.H. (2005). Changes in hydrologic regime by dams. *Geomorphology*, 71: 61-78.

Mann, H.B. (1945). Non-parametric tests against trend. *Econometrics*, 13: 245-259.

Marcé, R., Honey-Rosés, J., Manzano, A., Moragas, L., Catllar, B., Sabater, S. (2012). The Llobregat River Basin: A Paradigm of Impaired Rivers Under Climate Change Threats. In: Sabater, S., Ginebreda, A., Barceló, D. (eds): The Llobregat: *The Story of a Polluted Mediterranean River*. Spinger-Verlag: Berlin.

Mathews, R., Richter, B.D. (2007). Application of the indicators of hydrologic alteration software in environmental flow setting. *Journal of the American Water Resources Association*, 43 (6): 1400-1413.

Milliman, J.D. (2001). Delivery and fate of fluvial water and sediment to the sea: a marine geologist's view of European rivers. *Scientia Marina*, 65 (suppl. 2): 121-132.

Milliman, J.D., Farnsworth, K.L., Jone, P.D., Xu, K.H., Smith, L.C. (2008). Climatic and anthropogenic factors affecting river discharge to the global ocean, 1951-2000. *Global and Planetary Change*, 62: 187-194.

Nislow, K.H., Magilligan, F.J., Fassnacht, H., Bechtel, D., Ruesink, A. (2002). Effects of dam impoundment on the flood regime of natural floodplain communities in the upper Connecticut river. *Journal of the American Water Resources Association*, 38 (6): 1533-1548.

Petts, G.E. (1984). *Impounded Rivers. Perspectives for Ecological Management*. Wiley: New York; 326 pp.

Ponsatí, L., Acuña, V., Aristi, I., Arroita, M., García-Berthou, E., von Schiller, D., Elosegui, A., Sabater, S. (2014). Biofilm responses to flow regulation by dams in Mediterranean rivers. *River Research and Applications*, 31 (8): 1003-1016.

Pyron, M., Neumann, K. (2008). Hydrologic alterations in the Wabash river watershed, USA. *River Research and Applications*, 24 (8): 1175-1184.

Richter, B.D., Baumgartner, J.V., Powell, J., Braun, D.P. (1996). A method for assessing hydrologic alteration within ecosystems. *Conservation Biology*, 10 (4): 1163-1174.

Sabater, S., Artigas, J., Durán, C., Pardos, M., Romaní, A.M., Tornés, E., Ylla, I. (2008). Longitudinal development of chlorophyll and phytoplankton assemblages in a regulated large river (the Ebro River). *Science of the Total Environment*, 404 (1): 196-206.

Singer, M.B. (2007). The influence of major dams on hydrology through the drainage network of the Sacramento river basin, California. *River Research and Applications*, 23: 55-72.

The Nature Conservancy. (2009). *Indicators of Hydrologic Alteration Version 7.1*. User's Manual.

USACE. (1993). *Hydrologic Frequency Analysis*. Engineering Manual EM1110-2-1415. U.S. Army Corps of Engineers: Washington, D.C.

Vericat, D., Batalla, R.J. (2005). Sediment transport in a highly regulated fluvial system during two consecutive floods (lower Ebro River, NE Iberian Peninsula). *Earth Surface Processes and Landforms*, 30 (4): 385-402.

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

Votruba, L., Broža, V. (1989). *Water Management in Reservoirs*. Elsevier: New York.

Wainwright, J., Thornes, J.B. (2004). *Environmental Issues in the Mediterranean. Processes and Perspectives from the Past and Present*. Routledge: London; 512 pp.

Ward, J.A., Stanford, J.A. (1979). *The Ecology of Regulated Streams*. Plenum Press: New Cork.

Williams, G.P., Wolman, M.G. (1984). *Downstream effects of dams on alluvial fans*. US Geological Survey Professional Paper, 1286.

Yang, S.L., Xu, K.H., Milliman, J.D., Yang, H.F., Wu, C.S. (2015). Decline of Yangtze River water and sediment discharge: impact from natural and anthropogenic changes. *Scientific Reports*, 5: 12581.

SUPPORTING INFORMATION 1

Table S3.1. Land use changes in the studied Mediterranean basins between the years 1990 and 2006.

			Agriculture	Grassland and scrubland	Woodland	Improductive	Urban	Water
ORB	**Surface (km^2)**	**1990**	494.2	121.6	899.2	44.7	17.5	8.2
		2006	495.6	107.1	901.3	52.0	21.8	7.7
	% change		0.3	-12.0	0.2	16.3	24.4	-7.0
AUDE	**Surface (km^2)**	**1990**	2,462.9	457.5	2,247.0	105.7	21.7	35.6
		2006	2,445.0	374.2	2,331.9	115.8	27.3	35.7
	% change		-0.7	-18.2	3.8	9.6	26.3	0.2
AGLY	**Surface (km^2)**	**1990**	290.7	67.9	674.0	15.2	7.2	0.2
		2006	272.3	77.1	679.7	14.7	9.6	1.9
	% change		-6.3	13.6	0.9	-3.4	34.1	717.4
TÊT	**Surface (km^2)**	**1990**	266.2	307.4	711.9	69.7	10.9	4.8
		2006	257.0	285.7	738.7	71.9	12.7	4.8
	% change		-3.5	-7.1	3.8	3.2	16.4	-0.6
TECH	**Surface (km^2)**	**1990**	127.2	98.0	471.7	20.9	3.8	0.1
		2006	128.7	75.5	488.7	22.6	6.2	0.1
	% change		1.1	-23.0	3.6	8.2	60.7	0.0
MUGA	**Surface (km^2)**	**1990**	243.2	12.9	484.3	12.5	1.6	3.5
		2006	238.2	11.9	484.8	12.8	6.9	3.5
	% change		-2.0	-7.9	0.1	1.8	324.1	-0.6
FLUVIÀ	**Surface (km^2)**	**1990**	254.4	19.9	687.2	9.1	0.6	0.9
		2006	252.1	20.0	686.4	11.2	1.6	0.9
	% change		-0.9	0.5	-0.1	22.6	181.8	-2.2
TER	**Surface (km^2)**	**1990**	813.6	251.3	1,787.4	84.8	9.7	19.0
		2006	797.3	249.6	1,784.4	94.2	21.4	19.0
	% change		-2.0	-0.7	-0.2	11.0	121.5	-0.1
CARDENER	**Surface (km^2)**	**1990**	369.4	48.0	861.1	49.8	4.5	1.5
		2006	368.3	47.9	878.9	30.9	5.2	3.2
	% change		-0.3	-0.3	2.1	-38.0	16.8	115.3
LLOBREGAT*	**Surface (km^2)**	**1990**	1,117.2	136.7	1,952.2	339.7	43.6	6.3
		2006	1,089.4	130.4	2,082.9	208.2	78.9	5.8
	% change		-2.5	-4.6	6.7	-38.7	81.1	-7.5
FOIX	**Surface (km^2)**	**1990**	161.3	0.4	112.5	35.6	2.1	0.8
		2006	157.8	0.4	133.1	16.4	4.4	0.8
	% change		-2.2	0.0	18.3	-54.1	104.7	0.0
SIURANA	**Surface (km^2)**	**1990**	214.1	0.3	390.2	6.6	0.0	0.8
		2006	212.7	0.3	393.4	4.6	0.0	1.1
	% change		-0.6	0.0	0.8	-30.1	0.0	35.9

SUPPORTING INFORMATION 2

Table S3.2. Flow percentiles for daily flows for altered and non-altered sites.

		P_5	P_{16}	P_{50}	P_{84}	P_{95}
Regulated						
ORB	**Y2504010***	0.28	0.35	0.67	2.35	6.15
	Y2504020	0.70	0.96	2.60	5.20	11.20
	Y2514020	*1.42*	*1.94*	*4.27*	*9.41*	*22.20*
	Y2554010	*4.04*	*5.28*	*12.50*	*35.20*	*78.13*
	Y2584010	*4.15*	*6.00*	*14.10*	*36.09*	*79.47*
AUDE	**Y1112010***	4.40	5.30	11.70	24.10	34.50
	Y1112010 (Alt1)	4.70	6.00	11.20	21.60	33.40
	Y1112010 (Alt2)	3.36	5.25	10.00	20.32	30.75
	Y1232010	*3.68*	*5.75*	*12.50*	*31.60*	*52.60*
	Y1612010	*5.09*	*8.00*	*25.00*	*67.00*	*128.00*
AGLY	**Y0624020***	0.29	0.43	1.20	3.77	9.13
	Y0634030	0.47	0.72	1.86	4.49	10.60
	Y0664040	*0.00*	*0.00*	*0.87*	*5.26*	*13.72*
TÊT	**Y0424010***	1.58	2.21	4.04	7.55	11.9
	Y0464050	2.84	4.27	7.08	15.1	29.6
	Y0474040	*1.09*	*1.82*	*4.84*	*15.8*	*36.45*
MUGA	**EA012***	0.35	0.54	0.95	2.98	6.93
	EA012	0.16	0.28	1.05	3.44	6.12
	EA052	*0.16*	*0.32*	*0.76*	*2.22*	*9.80*
TER	**EA019***	2.76	4.50	7.88	19.43	40.00
	EA010	3.29	4.71	7.78	21.35	50.82
CARDENER	**EA025***	0.69	1.05	2.22	4.90	9.17
	EA001	1.18	1.60	2.90	5.94	11.89
	EA002	*2.00*	*2.76*	*4.46*	*9.41*	*17.56*
LLOBREGAT	**EA078***	0.90	1.32	2.78	8.13	17.12
	EA066	2.94	3.90	5.51	8.95	20.60
	EA067	*2.03*	*3.26*	*5.35*	*9.26*	*19.02*
	EA031	*3.45*	*4.37*	*6.80*	*14.95*	*34.00*
	EA023*	3.91	5.38	8.50	20.75	38.10
	EA023 (Alt1)	*4.64*	*6.32*	*11.52*	*28.50*	*54.50*
	EA023 (Alt2)	*5.70*	*7.30*	*11.35*	*23.60*	*42.00*
	EA005*	5.30	6.80	10.16	24.05	45.84
	EA005 (Alt1)	*4.07*	*6.18*	*13.85*	*39.46*	*76.73*
	EA005 (Alt2)	*4.25*	*5.80*	*9.45*	*23.46*	*47.94*
SIURANA	**EA041***	0.00	0.05	0.25	0.81	1.75
	EA041+C4042	0.00	0.03	0.12	0.62	1.57
Non-regulated						
TECH	**Y0254040**	1.24	1.88	3.97	10.50	21.50
FLUVIÀ	**EA016**	1.07	1.78	3.86	8.08	15.25
FOIX	**EA008**	0.00	0.00	0.07	0.33	0.99

* Data from non-regulated gauging stations.

For basins where more than one reservoir is altering river flow, Alt1: period when only one dam was operating, Alt2: period when two dams were operating.
Data in italics correspond to data series used to assess recovery downstream.

SUPPORTING INFORMATION 3

Table S3.3. Discharge corresponding to 2-, 10- and 25-year return period and changes after dam construction

		Q_2 ($m^3/s{\cdot}km^2$)			Q_{10} ($m^3/s{\cdot}km^2$)			Q_{25} ($m^3/s{\cdot}km^2$)		
		Non-altered	**Altered**	***δ***	**Non-altered**	**Altered**	***δ***	**Non-altered**	**Altered**	***δ***
Regulated										
ORB	Y2504010	0.6	-	1.02	1.1	-	1.16	-	-	-
	Y2504020	-	0.61		-	1.28		-	-	
	Y2514020	-	*0.89*		-	*1.34*		-	-	
	Y2554010	-	*0.77*		-	*1.35*		-	-	
	Y2584010	-	*0.57*		-	*1.11*		-	-	
AUDE	Y1112010[a]	0.09	0.09	1.00	0.17	0.17	1.00	0.22	0.22	1.00
			0.09	1.00		0.19	1.12		0.25	1.14
	Y1232010	-	*0.11*		-	*0.28*		-	*0.36*	
	Y1612010	-	*0.09*		-	*0.17*		-	*0.22*	
AGLY	Y0624020	0.21	-	0.62	0.48	-	0.75	0.62	-	0.77
	Y0634030	-	0.13		-	0.36		-	0.48	
	Y0664040	-	*0.25*		-	*0.73*		-	*0.98*	
TÊT	Y0424010	0.06	-	1.50	0.14	-	1.29	0.18	-	1.22
	Y0464050	-	0.09		-	0.18		-	0.22	
	Y0474040	-	*0.12*		-	*0.28*		-	*0.36*	
MUGA	EA012	0.26	0.11	0.42	0.62	0.38	0.61	0.80	0.52	0.65
	EA052	-	*0.18*		-	*0.53*		-	*0.70*	
TER	EA019	0.13	-	0.46	0.24	-	0.63	0.30	-	0.67
	EA010	-	0.06		-	0.15		-	0.20	
CARDENER	EA025	0.11	-	0.45	0.20	-	0.85	0.25	-	0.92
	EA001	-	0.05		-	0.17		-	0.23	
	EA002	-	*0.04*		-	*0.12*		-	*0.16*	

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(Table S3.3 continued)

		Q_2 ($m^3/s \cdot km^2$)			**Q_{10} ($m^3/s \cdot km^2$)**			**Q_{25} ($m^3/s \cdot km^2$)**		
		Non-altered	**Altered**	**δ**	**Non-altered**	**Altered**	**δ**	**Non-altered**	**Altered**	**δ**
Regulated										
LLOBREGAT	EA078	0.19	-	0.42	0.48	-	0.63	0.63	-	0.67
	EA066	-	0.08		-	0.30		-	0.42	
	EA067	-	*0.06*		-	*0.19*		-	*0.26*	
	EA031	-	*0.06*		-	*0.16*		-	*0.21*	
	EA023[a]	*0.04*	*0.06*	*1.50*	*0.06*	*0.11*	*1.83*	*0.08*	*0.14*	*1.75*
		-	*0.04*	*0.88*	-	*0.13*	*2.10*	-	*0.17*	*2.15*
	EA005[a]	*0.04*	*0.06*	*1.50*	*0.07*	*0.12*	*1.71*	*0.08*	*0.15*	*1.88*
		-	*0.03*	*0.78*	-	*0.10*	*1.43*	-	*0.14*	*1.88*
SIURANA	EA041+C4042	0.17	0.04	0.24	0.42	0.20	0.48	0.54	0.29	0.54
Non-regulated										
TECH	Y0254040	0.35	0.37		0.96	0.77		1.26	0.97	
FLUVIÀ	EA016	0.11	0.19		0.29	0.41		0.39	0.52	
FOIX	EA008	0.05	0.03		0.18	0.07		0.25	0.09	

[a] Gauging stations with one pre-dam and two post-dam series.

Data in italics correspond to data series used to assess recovery downstream

SUPPORTING INFORMATION 4

Table S3.4. Changes in IHA parameters used to describe median duration and frequency of flows, mean up-ramp rate. (Part I)

		Median duration extremely low flows				**Median duration high flow pulses**				**Median duration small floods**			
		Non-altered		**Altered**		**Non-altered**		**Altered**		**Non-altered**		**Altered**	
		Days	**Disp.C**	**Days**	**Disp.C**	**Days**	**Disp.C**	**Days**	**Disp.C**	**Days**	**Disp.C**	**Days**	**Disp.C**
Regulated													
ORB	Y2504010	6.50	0.92	-	-	4.75	0.50	-	-	88.00	0.75	-	-
	Y2504020	-	-	4.00	0.38	-	-	2.75	1.64	-	-	40.00	2.43
	Y2514020	-	-	*3.50*	*2.71*	-	-	*4.00*	*1.75*	-	-	*65.00*	*0.88*
	Y2554010	-	-	*4.00*	*0.94*	-	-	*2.50*	*1.20*	-	-	*87.00*	*0.94*
	Y2584010	-	-	*3.75*	*1.00*	-	-	*3.00*	*1.21*	-	-	*88.00*	*0.94*
AUDE	Y1112010[a]	4.50	0.89	5.00	0.90	4.50	0.97	3.00	1.00	44.00	1.82	20.00	1.50
				2.00	1.00			3.00	0.67			35.00	1.46
	Y1232010	-	-	*2.00*	*0.75*	-	-	*3.00*	*0.67*	-	-	*36.50*	*1.94*
	Y1612010	-	-	*3.00*	*2.25*	-	-	*4.50*	*1.31*	-	-	*40.50*	*1.73*
AGLY	Y0624020	8.00	1.92	-	-	3.50	2.00	-	-	33.00	2.86	-	-
	Y0634030	-	-	36.00	1.52	-	-	8.00	0.66	-	-	93.75	0.69
	Y0664040	-	-	*19.00*	*1.63*	-	-	*4.50*	*1.75*	-	-	*91.00*	*0.99*
TÊT	Y0424010	2.00	0.44	-	-	2.00	0.88	-	-	52.50	1.12	-	-
	Y0464050	-	-	4.00	1.00	-	-	3.50	1.14	-	-	16.25	0.98
	Y0474040	-	-	*4.00*	*0.44*	-	-	*3.00*	*0.75*	-	-	*22.00*	*1.40*
MUGA	EA012	6.75	1.37	2.25	1.89	5.00	0.90	4.25	5.59	30.50	1.03	14.00	0.64
	EA052	-	-	*10.50*	*2.57*	-	-	*4.00*	*1.50*	-	-	*30.75*	*1.89*
TER	EA019	1.00	1.00	-	-	2.00	0.94	-	-	26.50	0.79	-	-
	EA010	-	-	3.75	3.23	-	-	2.00	0.75	-	-	37.50	1.95
CARDENER	EA025	5.00	1.95	-	-	4.00	0.75	-	-	27.00	1.07	-	-
	EA001	-	-	3.00	2.50	-	-	4.00	1.13	-	-	33.50	1.44
	EA002	-	-	*2.00*	*1.63*	-	-	*3.00*	*0.83*	-	-	*24.50*	*0.92*

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(Table S3.4 Part I continued)

		Median duration extremely low flows				Median duration high flow pulses				Median duration small floods			
		Non-altered		Altered		Non-altered		Altered		Non-altered		Altered	
		Days	**Disp.C**	**Days**	**Disp.C**	**Days**	**Disp.C**	**Days**	**Disp.C**	**Days**	**Disp.C**	**Days**	**Disp.C**
Regulated													
LLOBREGAT	EA078	4.50	1.56	-	-	5.00	1.05	-	-	25.00	0.92	-	-
	EA066	-	-	3.00	4.79	-	-	5.75	1.48	-	-	17.50	1.03
	EA067	-	-	*3.50*	*1.39*	-	-	*2.00*	*1.38*	-	-	*27.00*	*0.81*
	EA031	-	-	*2.00*	*0.88*	-	-	*3.00*	*1.08*	-	-	*42.00*	*1.34*
	EA023[a]	*8.50*	*0.79*	*2.00* *3.00*	*2.38* *0.67*	*2.75*	*0.36*	*5.00* *3.25*	*0.95* *1.69*	*20.00*	*4.00*	*34.00* *36.00*	*1.59* *0.59*
	EA005[a]	*3.50*	*2.43*	*2.00* *2.00*	*1.00* *0.50*	*10.00*	*0.40*	*9.00* *2.00*	*0.78* *0.75*	*27.00*	*2.07*	*30.00* *30.00*	*1.60* *1.09*
SIURANA	EA041+C40 42	6.00	2.04	11.00	9.64	7.00	1.43	5.50	0.70	41.75	1.06	11.75	0.90
Non-regulated													
TECH	Y0254040	3.00	1.92	-	-	4.00	1.00	-	-	22.00	0.81	-	-
FLUVIÀ	EA016	8.75	1.87	-	-	3.00	1.00	-	-	23.50	1.87	-	-
FOIX	EA008	15.50	1.03	-	-	2.00	1.00	-	-	8.00	8.94	-	-

[a] Gauging stations with one pre-dam and two post-dam series.

Data in italics correspond to data series used to assess recovery downstream.

Table S3.4. Changes in IHA parameters used to describe median duration and frequency of flows, mean up-ramp rate. (Part II)

		Median frequency high flow pulses				Mean up-ramp rate			
		Non-altered		Altered		Non-altered		Altered	
		Freq	Disp.C	Freq	Disp.C	m^3/day	SD	m^3/day	SD
Regulated									
ORB	Y2504010	8.50	0.44	-	-	1.91	0.6	-	-
	Y2504020	-	-	6.00	1.25	-	-	1.41	0.7
	Y2514020	-	-	*7.00*	*0.43*	-	-	*3.20*	*0.6*
	Y2554010	-	-	*9.00*	*0.78*	-	-	*9.94*	*0.5*
	Y2584010	-	-	*6.50*	*0.27*	-	-	*13.26*	*0.8*
AUDE	Y1112010[a]	8.50	0.68	6.00 7.50	1.33 0.87	3.35	0.3 7	3.49 2.22	0.5 0.4
	Y1232010	-	-	*7.00*	*1.00*	-	-	*5.62*	*0.6*
	Y1612010	-	-	*6.00*	*0.83*	-	-	*17.07*	*0.8*
AGLY	Y0624020	5.00	0.80	-	-	1.38	0.7	-	-
	Y0634030	-	-	2.00	2.00	-	-	1.22	0.8
	Y0664040	-	-	*3.00*	*1.33*	-	-	*4.78*	*1.0*
TÊT	Y0424010	8.00	0.63	-	-	0.73	0.3	-	-
	Y0464050	-	-	7.50	0.87	-	-	1.86	0.6
	Y0474040	-	-	*6.00*	*0.92*	-	-	*3.35*	*0.6*
MUGA	EA012	6.00	0.71	4.50	1.78	4.00	1.0	0.96	1.1
	EA052	-	-	*3.50*	*1.50*	-	-	*7.84*	*1.7*
TER	EA019	11.00	0.61	-	-	5.51	0.7	-	-
	EA010	-	-	7.00	1.29	-	-	3.34	0.8
CARDENER	EA025	8.00	0.50	-	-	1.14	0.4	-	-
	EA001	-	-	6.50	1.19	-	-	1.36	1.0
	EA002	-	-	*6.50*	*1.04*	-	-	*2.01*	*0.9*

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(Table S3.4 Part II continued)

		Median frequency high flow pulses				**Mean up-ramp rate**			
		Non-altered		**Altered**		**Non-altered**		**Altered**	
		Freq	**Disp.C**	**Freq**	**Disp.C**	**m^3/day**	**SD**	**m^3/day**	**SD**
Regulated									
LLOBREGA	EA078	6.00	0.83	-	-	1.94	0.6	-	-
	EA066	-	-	4.00	1.25	-	-	2.29	1.4
	EA067	-	-	*7.00*	*0.86*	-	-	*1.71*	*1.0*
	EA031	-	-	*8.00*	*0.88*	-	-	*2.97*	*0.8*
	EA023[a]	*10.00*	*0.40*	*6.00*	*0.67*	*7.16*	*0.4*	*9.87*	*0.7*
				5.00	*0.70*		*0*	*4.32*	*0.6*
	EA005[a]	*10.00*	*0.40*	*9.00*	*0.78*	*1.52*	*1.1*	*9.24*	*0.6*
				9.00	*0.83*		*7*	*4.43*	*0.6*
SIURANA	EA041+C40	5.00	0.80	5.00	0.80	0.67	0.6	0.46	2.2
Non-regulated									
TECH	Y0254040	7.00	0.57	-	-	4.11	1.0	-	-
FLUVIÀ	EA016	6.00	0.83	-	-	5.92	0.9	-	-
FOIX	EA008	8.00	0.75	-	-	0.79	0.9	-	-

[a] Gauging stations with one pre-dam and two post-dam series.

Data in italics correspond to data series used to assess recovery downstream.

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Table S3.5. Average of the monthly maximum flows ($m^3/s \cdot km^2$) for the altered and non-altered selected sites for the 9 regulated rivers.

		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
ORB	**Y2504010***	0.173	0.076	0.063	0.229	0.155	0.153	0.218	0.053	0.062	0.009	0.007	0.025
	Y2504020	0.078	0.022	0.017	0.139	0.075	0.103	0.138	0.057	0.040	0.022	0.023	0.029
	Y2514020	*0.130*	*0.050*	*0.037*	*0.177*	*0.080*	*0.155*	*0.132*	*0.045*	*0.033*	*0.015*	*0.014*	*0.028*
	Y2554010	*0.121*	*0.080*	*0.085*	*0.173*	*0.099*	*0.182*	*0.191*	*0.064*	*0.045*	*0.014*	*0.010*	*0.054*
	Y2584010	*0.118*	*0.051*	*0.051*	*0.169*	*0.072*	*0.146*	*0.163*	*0.040*	*0.027*	*0.010*	*0.009*	*0.042*
AUDE	**Y1112010***	0.041	0.039	0.041	0.035	0.051	0.043	0.047	0.060	0.049	0.031	0.017	0.015
	Y1112010 (Alt1)	0.028	0.026	0.033	0.033	0.046	0.038	0.056	0.064	0.044	0.024	0.021	0.025
	Y1112010 (Alt2)	0.020	0.030	0.041	0.036	0.034	0.044	0.049	0.057	0.037	0.020	0.015	0.020
	Y1232010	*0.023*	*0.023*	*0.036*	*0.043*	*0.038*	*0.050*	*0.052*	*0.057*	*0.026*	*0.010*	*0.007*	*0.010*
	Y1612010	*0.030*	*0.012*	*0.024*	*0.037*	*0.039*	*0.049*	*0.042*	*0.037*	*0.015*	*0.006*	*0.004*	*0.009*
AGLY	**Y0624020***	0.055	0.059	0.105	0.062	0.053	0.095	0.058	0.066	0.023	0.006	0.006	0.008
	Y0634030	0.024	0.011	0.066	0.029	0.029	0.066	0.037	0.042	0.012	0.005	0.006	0.005
	Y0664040	*0.027*	*0.091*	*0.105*	*0.019*	*0.025*	*0.069*	*0.049*	*0.027*	*0.007*	*0.002*	*0.003*	*0.001*
TÊT	**Y0424010***	0.021	0.031	0.021	0.016	0.014	0.017	0.022	0.035	0.032	0.018	0.014	0.015
	Y0464050	0.028	0.033	0.033	0.032	0.017	0.018	0.028	0.041	0.030	0.014	0.011	0.013
	Y0474040	*0.030*	*0.040*	*0.055*	*0.041*	*0.026*	*0.023*	*0.030*	*0.044*	*0.022*	*0.007*	*0.005*	*0.016*
MUGA	**EA012***	0.109	0.097	0.061	0.032	0.076	0.079	0.051	0.044	0.025	0.015	0.017	0.079
	EA012	0.011	0.009	0.048	0.062	0.038	0.030	0.033	0.039	0.028	0.025	0.021	0.016
	EA052	*0.034*	*0.032*	*0.052*	*0.069*	*0.082*	*0.043*	*0.040*	*0.027*	*0.006*	*0.002*	*0.002*	*0.005*
TER	**EA019***	0.032	0.029	0.065	0.043	0.033	0.029	0.024	0.028	0.023	0.014	0.012	0.011
	EA010	0.027	0.022	0.043	0.025	0.015	0.016	0.016	0.030	0.022	0.012	0.008	0.014
CARDENER	**EA025***	0.040	0.046	0.037	0.037	0.027	0.041	0.036	0.043	0.038	0.020	0.026	0.028
	EA001	0.015	0.027	0.020	0.017	0.012	0.021	0.016	0.022	0.014	0.008	0.010	0.012
	EA002	*0.013*	*0.020*	*0.013*	*0.012*	*0.009*	*0.014*	*0.013*	*0.017*	*0.012*	*0.006*	*0.007*	*0.012*

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(Table S3.5 continued)

		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
LLOBREGAT	**EA078***	0.080	0.074	0.091	0.044	0.028	0.041	0.048	0.069	0.055	0.026	0.027	0.036
	EA066	0.024	0.062	0.030	0.037	0.024	0.021	0.028	0.037	0.032	0.021	0.015	0.015
	EA067	*0.012*	*0.032*	*0.024*	*0.020*	*0.012*	*0.014*	*0.017*	*0.025*	*0.025*	*0.016*	*0.010*	*0.010*
	EA031	*0.017*	*0.031*	*0.025*	*0.021*	*0.015*	*0.012*	*0.015*	*0.020*	*0.017*	*0.012*	*0.007*	*0.008*
	EA023*	0.012	0.006	0.006	0.004	0.005	0.016	0.009	0.023	0.016	0.009	0.015	0.014
	EA023 (Alt1)	*0.016*	*0.023*	*0.017*	*0.010*	*0.013*	*0.026*	*0.021*	*0.022*	*0.013*	*0.008*	*0.013*	*0.031*
	EA023 (Alt2)	*0.014*	*0.026*	*0.022*	*0.013*	*0.011*	*0.009*	*0.010*	*0.014*	*0.015*	*0.007*	*0.006*	*0.008*
	EA005*	0.015	0.005	0.005	0.003	0.004	0.013	0.008	0.022	0.016	0.010	0.019	0.018
	EA005 (Alt1)	*0.017*	*0.022*	*0.021*	*0.011*	*0.011*	*0.026*	*0.018*	*0.021*	*0.013*	*0.007*	*0.011*	*0.032*
	EA005 (Alt2)	*0.009*	*0.019*	*0.017*	*0.011*	*0.009*	*0.008*	*0.009*	*0.013*	*0.010*	*0.006*	*0.004*	*0.009*
SIURANA	**EA041***	0.056	0.026	0.038	0.014	0.013	0.049	0.037	0.037	0.021	0.007	0.009	0.035
	EA041	0.009	0.010	0.027	0.007	0.007	0.008	0.009	0.012	0.015	0.014	0.014	0.011

* Data from non-regulated gauging stations.
For basins where more than one reservoir is altering river flow, Alt1: period when only one dam was operating, Alt2: period when two dams were operating.
Data in italics correspond to data series used to assess recovery downstream.