2D modelling of Ribarroja reservoir sedimentation in Ebro river

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Sediment transport and deposition is a known phenomenon that occur in dams. This has a significant impact on the dam’s storing capacity, and also quality of water upstream the dam, and a negative ecological impact downstream the dam.

The aim of this Master’s thesis is to study the dynamic of sediment of “Ribarroja” reservoir via mathematical modelling, for a better water and sediment management.

In this work the tool that has been used is the freeware package which is based on the solution of the two-dimensional shallow water equations using the finite volume method.
To my Father and Mother
ACKNOWLEDGMENTS

This project would not have been possible without the support of many people. Many thanks to my supervisors, Martí Sanchez, and Younes Salami, whom read my numerous revisions and helped make some sense of the confusion. Thanks to the Universitat Politècnica de Catalunya for awarding me a Dissertation Completion Fellowship, providing me with the financial means to complete this project. And finally, thanks to my parents who endured this long process with me, always offering support and love.
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CHAPTER I: INTRODUCTION

Siltation in reservoir dams is one of the main problems that meet many dams in the world. According to the report published by the International Commission on Large Dams (ICOLD), more than 50,000 large dams exist in the world with a very large storage capacity, operated for purposes such as water supply, hydroelectric power generation and flood control. On the other hand, an average rate of 0.5 to 1% of their storage capacity is lost each year due to sedimentation. In order to compensate for this reduction, 300 and 400 large dams must be built each year. So, the methods of appropriate treatment are strongly suggested to treat this problem while paying particular attention to the problem.

These quantities of sediments discharged by the dredging operations and deposited at upstream of the structure can lead to long-term environmental pollution. For this, the recovery and reuse of these sediments should allow in the medium term its valuation in the field of Civil Engineering: Road technology, brick making and grouting networks. As we can see the issue of sediment is a real challenge for water management, that's what made me choose this subject for my master thesis.

The area that we are going to study is the Ebro River basin, there are more than 109 reservoirs with greater capacity than 1 hm³ and about 800,000 ha of irrigated land (Prats et al. 2007). Ribarroja Reservoir is located in the lower Ebro River (41° 180 N, 0° 210 E) in the Mequinenza-Ribarroja-Flix hydropower system. The upstream reservoir is Mequinenza (1534 hm³) and the downstream one is Flix (11.4 hm³). In the tail of Ribarroja Reservoir there is the Segre River mouth. Segre River is one of the main tributaries of Ebro River, which provides almost half of the Ribarroja Reservoir inflow depending on the period of the year.

Ribarroja Dam was finished in 1969 and since then it is used for energy generation, water supply and irrigation in addition to flood control (LIMNOS 1996). Ribarroja Reservoir has an irregular morphology (Fig.1.) due to the surrounding topography, and its maximum volume is estimated to be 210 hm³. The residence time is about 6 to 10 days.
According to the Ebro River Water Authority (http://www.chebro.es), Ebro River has an average annual contribution of 8,009 hm³ to Ribarroja Reservoir. Segre River increases this contribution to 14,069 hm³. This means that Ebro River contributes on average 58.82% of the inflows to Ribarroja Reservoir, while Segre inputs are 41.15% (Prats-Rodríguez et al. 2011). There is also a small stream, Matarraña River, with a very limited flow contribution.

Fig. 1: Study area

The aim of this work, is to study the sediment behaviour along Ribarroja reservoir. The procedure followed in this study is as follows:

- Data analysis of the different gauge stations in the zone of study (Mequinenza, Ribarroja, Segre, and Sinca), in order to obtain the yearly average of each station from 1964 to 2015.
- Estimation of the average yearly hydrograph of each gauge station
- Run the hydrodynamic simulation of Ribarroja reservoir by means of Iber software
- Results discussion
1 Sediment Transport and Deposition:

1.1 Sediment

Sediment refers to the conglomerate of materials, organic and inorganic, that can be carried away by water, wind or ice Langland, M., & Cronin, T. (Eds.). (2003). While the term is often used to indicate soil-based, mineral matter (e.g. clay, silt and sand), decomposing organic substances and inorganic biogenic material are also considered sediment Wetzel, R. G. (2001). Most mineral sediment comes from erosion and weathering, while organic sediment is typically detritus and decomposing material such as algae EPA. (2014).

Fig. 2: Suspended Sediment vs Suspended Solids
These particulates are typically small, with clay defined as particles less than 0.00195 mm in diameter, and coarse sand reaching up only to 1.5 mm in diameter Osmond et al (1995). However, during a flood or other high flow event, even large rocks can be classified as sediment as they are carried downstream Perlman, H. (2014). Sediment is a naturally occurring element in many bodies of water, though it can be influenced by anthropogenic factors EPA. (2012).

In an aquatic environment, sediment can either be suspended (floating in the water column) or bedded (settled on the bottom of a body of water). When both floating and settled particles are monitored, they are referred to as SABS: Suspended And Bedded Sediments EPA. (2014).

Fine sediment can be found in nearly any body of water, carried along by the water flow. When the sediment is floating within the water column it is considered suspended. In this application, the terms “suspended sediment” and “suspended solids” are nearly interchangeable. The main difference between the two is in the method of measurement Gray, J. R. et al (2000).

Despite the similarity in meaning, the data provided by the different measurement methods are neither interchangeable nor comparable Gray, J. R. et al (2000). The suspended sediment concentration (SSC) is in mg/L by filtering and drying an entire water sample. Total suspended solids (TSS), while also measured in mg/L, are obtained by subsampling. While acceptable for homogenized or well mixed samples with very fine sediment, the TSS measurement often excludes larger suspended particles, like sand Gray, J. R. et al (2000). This means that the SSC measurement tends to be higher and more representative of a water body as a whole, often measuring within 5% of the true particle concentration Gao, Q. (2006). Due to the incomparability between suspended sediment measurements and total suspended solids measurements, the U.S. Geological Survey recommends SSC analysis over TSS when sampling in surface water Gray, J. R. et al (2000).

### 1.2 Sediment transport

Sediment transport is the movement of organic and inorganic particles by water Czuba, J. A. (2011). In general, the greater the flow, the more sediment that will be conveyed. Water flow
can be strong enough to suspend particles in the water column as they move downstream, or simply push them along the bottom of a waterway Southard, J. (2006). Transported sediment may include mineral matter, chemicals and pollutants, and organic material.

Another name for sediment transport is sediment load. The total load includes all particles moving as bedload, suspended load, and wash load Southard, J. (2006).

Bedload is the portion of sediment transport that rolls, slides or bounces along the bottom of a waterway EPA. (2012). This sediment is not truly suspended, as it sustains intermittent contact with the streambed, and the movement is neither uniform nor continuous Southard, J. (2006). Bedload occurs when the force of the water flow is strong enough to overcome the weight and cohesion of the sediment EPA. (2012). While the particles are pushed along, they typically do not move as fast as the water around them, as the flow rate is not great enough to fully suspend them Southard, J. (2006). Bedload transport can occur during low flows (smaller particles) or at high flows (for larger particles). Approximately 5-20% of total sediment transport is bedload Czuba, J et al (2011). In situations where the flow rate is strong enough, some of the smaller bedload particles can be pushed up into the water column and become suspended.

While there is often overlap, the suspended load and suspended sediment are not the same thing. Suspended sediment are any particles found in the water column, whether the water is flowing or not. The suspended load, on the other hand, is the amount of sediment carried downstream within the water column by the water flow Southard, J. (2006). Suspended loads require moving water, as the water flow creates small upward currents (turbulence) that keep the particles above the bed Hickin, E. J. (Ed.). (1995). The size of the particles that can be carried as suspended load is dependent on the flow rate Southard, J. (2006). Larger particles are more likely to fall through the upward currents to the bottom, unless the flow rate increases, increasing the turbulence at the streambed. In addition, suspended sediment will not necessarily remain suspended if the flow rate slows.

The wash load is a subset of the suspended load Hickin, E. J. (Ed.). (1995). This load is comprised of the finest suspended sediment (typically less than 0.00195 mm in diameter). The wash load is differentiated from the suspended load because it will not settle to the bottom of a waterway during a low or no flow period Southard, J. (2006). Instead, these particles remain in
permanent suspension as they are small enough to bounce off water molecules and stay afloat Southard, J. (2006). However, during flow periods, the wash load and suspended load are indistinguishable.

Turbidity in lakes and slow-moving rivers is typically due the wash load EPA. (2012). When the flow rate increases (increasing the suspended load and overall sediment transport), turbidity also increases. While turbidity cannot be used to estimate sediment transport, it can approximate suspended sediment concentrations at a specific location Fink, J. C. (2005).

*Fig. 3: Intersection between Mequinenza and Segre (by Prof. Ernest Bladé)*

### 1.3 Sediment deposition

Sediment is necessary to the development of aquatic ecosystems through nutrient replenishment and the creation of benthic habitat and spawning areas Czuba, J. A. et al (2011). These benefits occur due to sediment deposition – when suspended particles settle down to the bottom of a body of water. This settling often occurs when water flow slows down or stops, and heavy particles can no longer be supported by the bed turbulence. Sediment deposition can be found
anywhere in a water system, from high mountain streams, to rivers, lakes, deltas and floodplains. However, it should be noted that while sediment is important for aquatic habitat growth, it can cause environmental issues if the deposition rates are too high, or too low.

The suspended particles that fall to the bottom of a water body are called settleable solids Czuba, J. A. et al (2011). As they are found in riverbeds and streambeds, these settled solids are also known as bedded sediment EPA. (2012). The size of settleable solids will vary by water system – in high flow areas, larger, gravel-sized sediment will settle out first. Finer particles, including silt and clay, can be carried all the way out to an estuary or delta Oberrecht, K. (2011).

In marine environments, nearly all suspended sediment will settle. This is due to the presence of salt ions in the water. Salt ions bond to the suspended particles, encouraging them to combine with other particles in the water Hakanson, L. (2005). As the collective weight increases, the sediment begins to sink to the seafloor. This is why oceans and other marine ecosystems tend to have lower turbidity levels (greater water clarity) than freshwater environments Hakanson, L. (2005).

While estuaries and other tidal areas may be considered marine, they are not necessarily clearer than freshwater. Estuaries are the collection point for suspended sediment coming down river. Furthermore, in a tidal zone, the constant water movement causes the bottom sediment to continually resuspend, preventing high water clarity during tidal periods MDDNR. (n.d.). (2004). The clarity of an estuary will depend on its salinity level, as this will assist with particle deposition Oberrecht, K. (n.d.). (2011).

1.4 Factors that Influence Sediment Transport

Sediment transport is not constant. In fact, it is constantly subject to change. In addition to the changes in sediment load due to geology, geomorphology and organic elements, sediment transport can be altered by other external factors. The alteration to sediment transport can come from changes in water flow, water level, weather events and human influence.
1.4.1 Water Flow rate

Water flow rate, also called water discharge, is the single most important element of sediment transport. The flow of water is responsible for picking up, moving and depositing sediment in a waterway Missouri DNR. (2009). Without flow, sediment might remain suspended or settle out – but it will not move downstream. Flow is required to initiate the transport McNally, W. H., & Mehta, A. J. (2004). There are two basic ways to calculate flow. Water discharge can be simplified as area (a cross-section of the waterway) multiplied by velocity, or as a volume of water moved over time The University of Arizona. (2009).

\[ Q = A \cdot v \]

The equations describing the relationship of water flow and sediment transport are a bit more complex. The complexity of sediment transport rates is due to a large number of unknowns Fig. 4: relationship between velocity and particle diameter influencing the sediment transfer

(e.g. bed geometry, particle size, shape and concentration), as well as multiple forces acting upon the sediment (e.g. relative inertia, turbulent eddies, velocity fluctuations in speed and direction) Southard, J. (2006, Fall). The sediment transport rate in particular is difficult to measure, as any measurement method will disturb the flow and thus alter the reading. Most flow rate and sediment transport rate equations attempt to simplify the scenario by ignoring the effects of channel width, shape and curvature of a channel, sediment cohesion and non-uniform flows Southard, J. (2006, Fall). The two main flow factors in sediment transport are the settling rate and the boundary layer shear stress Crone, T. (2004, November). The settling rate (also
called Stokes settling) is the rate at which sediment falls through a liquid and it is controlled by the drag force (keeping a particle suspended) and the gravitational force (a function of the particle size) Crone, T. (2004, November). Understanding this relationship helps to define some of the forces that sediment transport has to overcome relative to particle size.

\[
V_S = \frac{(g \cdot (\rho_p - \rho_f) \cdot D_p^2)}{18 \mu} \tag{2}
\]

\(V_S\) = settling velocity  
\(g\) = gravitational constant  
\(\rho_p\) = particle density  
\(\rho_f\) = fluid density  
\(D_p\) = particle diameter  
\(\mu\) = fluid viscosity

Shear stresses in the boundary layer of a sediment bed explain how much force is required for water flow to overcome relative inertia and begin sediment transport (through bedload or suspended load) Crone, T. (2004, November).

\[
\tau = \rho_f \cdot u^*^2 \tag{3}
\]

\(\tau\) = shear stress  
\(\rho_f\) = fluid density  
\(u^*\) = characteristic velocity of turbulent flow (shear velocity)

In a basic freshwater river system, \(u^*\) can be calculated as:

\[
u_*=\sqrt{g \cdot h \cdot S} \tag{4}\]

\(u_*\) = shear velocity  
\(h\) = river depth  
\(g\) = gravitational constant  
\(S\) = river slope
To further understand the conditions required for sediment transport, the Shields stress equation can be used. Shields stress, along with the particle Reynolds number, can be used to predict how much flow is required for substantial sediment transport Crone, T. (2004, November). The Reynolds number is an expression of a particle’s resistance to viscous force Benson, T. (2014, June). In other words, the Reynolds number demonstrates whether or not a flow is viscous enough to overcome the relative inertia of sediment. For sediment transport, the Reynolds number for flow through a sediment bed can be calculated from the boundary layer shear stress equation:

$$Re_p = \frac{(u* \cdot Dp)}{v} \quad [5]$$

$Re_p$ = Reynolds number of the particle
$u*$ = characteristic velocity of turbulent flow (shear velocity)
$Dp$ = particle diameter
$v$ = kinematic viscosity (viscosity/ fluid density, $(\mu/\rho_f)$)

The point at which water flow begins to transport sediment is called the critical Shields stress Crone, T. (2004, November). This creates an empirical curve to approximate at what flow rate a sediment particle will move (based on particle size) Crone, T. (2004, November).

$$\tau* = \frac{\tau}{g \cdot (\rho_p - \rho_f) \cdot D_p} \quad [6]$$

$\tau*$ = Shields stress
$\tau$ = shear stress
$g$ = gravitational constant
$\rho_p$ = particle density
$\rho_f$ = density of fluid
$D_p$ = particle diameter
While these equations help define minimum flow rates for sediment transportation, they do not determine sediment load and sediment transport rates themselves. One sediment transport rate equation was developed by van Rijn, for the bedload transport of particles between 0.2-2mm.

\[ q_b = 0.053 \cdot [(s - 1) \cdot g]^{0.5} \cdot d_{50}^{1.5} \cdot \left[ \frac{T^*}{D^*} \right]^{2.1/0.3} \]  

$q_b$ = bedload transport rate  
$s$ = specific density of sediment  
$g$ = gravitational constant  
$d_{50}$ = median particle diameter  
$T^*$ = transport stage parameter  
$D^*$ = dimensionless grain size

The suspended load transport rate (still assuming cohesionless sediment and a sediment size of 0.2-2mm) is even more complicated:
\[ q_s = u \cdot h \cdot c_a \cdot \left[ \frac{\left( \frac{a}{h} \right)^{Z'} - \left( \frac{a}{h} \right)^{1.2}}{\left( 1 - \frac{a}{h} \right)^{Z'} \cdot (1.2 - Z')} \right] \] 

\[ q_s = suspended \ load \ transport \ rate \quad a = height \ above \ the \ bed, \ relative \ to \ particle \ size \]
\[ u = average \ flow \ velocity \]
\[ h = average \ flow \ depth \]
\[ c_a = \text{reference concentration} \]
\[ Z' = \text{suspension number} \]

Other sediment rating curves have been developed, but they cannot be equally applied to all water bodies Hickin, E. J. (Ed.). (1995). This is because in any application, there are seven main variables that have an effect on sediment transport rates Southard, J. (2006, Fall). Wilcock, P., et al ((2009, May).

\[ q_s = f(\tau, h, D, \rho_p, \rho_f, \mu, g) \] 

\[ q_s = \text{sediment transport rate per unit width} \]
\[ \tau = \text{shear stress} \]
\[ h = \text{depth} \]
\[ D = \text{particle diameter} \]
\[ \rho_p = \text{particle density} \]
\[ \rho_f = \text{fluid density} \]
\[ \mu = \text{water viscosity} \]
\[ g = \text{gravitational constant} \]

The sediment transport rate is a function of these seven variables, as well as the size-shape-density distribution (often assumed as a standard deviation of the particle diameter) of the suspended particles Wilcock, P., et al ((2009, May). In addition, the largest river discharge does not automatically mean that a river will have the largest sediment load. The quantity and
material of the sediment particles, as well as the geography of the local terrain will still play a contributing role in the sediment load Czuba, J. A., et al ((2011, August).
The sediment load itself is calculated as a depth-integrated sediment mass above a unit area Southard, J. (2006, Fall). It is variable for multiple reasons but can be estimated with a time-average collected sediment concentration Southard, J. (2006, Fall). While it is dependent on flow to initiate and continue transport, it is not calculated from flow rates, as the main variables in sediment load come from environment factors.

2 Hydrograph analysis:

The various contributing components of a natural hydrograph are shown in Fig. 6 To begin with there is base-flow only, the groundwater contribution from the aquifers bordering the river which go on discharging more and more slowly with time. The hydrograph of base-flow is near to an exponential curve and the quantity at any time may be represented very nearly by:

\[ Q_e = Q_0 e^{-\alpha t} \]  \hfill [10]

\( Q_0 \) = discharge at start of period \hspace{1cm} \( \alpha \) = coefficient of aquifer
\( Q_t \) = discharge at end of time t \hspace{1cm} \( e \) = base of natural logarithm

Fig. 6: Component parts of a natural hydrograph
As soon as rainfall begins there is an initial period of interception and infiltration before any measurable runoff reaches the stream channels and during the period of rain these losses continue in a reduced form as discussed previously, so that the rain graph has to be adjusted to show nett, or effective rain. When the initial losses are met, surface runoff begins and continues to a peak value which occurs at a time $t_p$, measured from the centre of gravity of the rain graph of nett rain. Thereafter it declines along the recession limb until it completely disappears. Meantime the infiltration and percolation which has been continuing during the gross rain period results in an elevated groundwater table which therefore contributes more at the end of the storm flow than at the beginning, but thereafter is again declining along its depletion curve. Surface runoff is, for convenience, assumed to contain two other components; channel precipitation and inter flow. Channel precipitation is that portion of the total catchment precipitation that falls directly on the stream, river and lake surfaces. It is usually small but if large lakes are present in the catchment it may be quite important and then requires separate treatment. Inter flow refers to water travelling horizontally through the upper horizons of the soil, perhaps in artificial tile drain systems or above hard-pans or impermeable layers immediately below the surface. Such flow can vary from nothing to appreciable fractions of total runoff. Since the groundwater contribution to flood flow is quite different in character from surface runoff it should be analysed separately and one of the first requirements in hydrograph analysis therefore is to separate these two.

3 Study area:
As it was mentioned in the introduction and shown in Fig. 1, the Ribarroja reservoir is the study area. The Ribarroja Reservoir is located immediately downstream of Mequinenza Reservoir, which is the largest reservoir in Ebro River. Both reservoirs are situated in the lower Ebro River, being the Ribaroja Dam at a distance of 115 km to the river mouth. Ribarroja is a monomythic long and narrow reservoir with a fairly regular morphology. The present storage capacity is of 1590 hm³. Its residence time is about a few weeks. Ribarroja Reservoir is closed downstream by a gravity dam with its crest at an elevation of 76 m above the sea and the base at 16 m.

3.1 Station:
The gauging stations in the study area are four. They are:

- Outlet in Mequinenza dam
- Outlet in Ribarroja dam
- Cinca river in the Ebro catchment basin
- Segre river in the Ebro catchment basin

3.1.1 Gauging station of Mequinenza:

The Mequinenza dam is located on the Ebro, in Spain in the province of Zaragoza and Huesca, in Aragon. Its reservoir, known as the "Sea of Aragon" extends over the provinces of Zaragoza and Huesca.

The reservoir is 120 km long, from Caspe to Mequinenza. Its maximum width is 600 m for a total area of 7,720 km².

Identification

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| State | High | Start | 1964 | Cota (m) |
3.1.2 Gauging station of Cinca:

The Cinca is a river in Aragon, Spain. Its source is in the Circo de Pineta, in the Ordesa y Monte Perdido National Park, in the Aragonese Pyrenees. It is a tributary to the Segre River, with its confluence at La Granja d’Escarp, not far from the point where the Segre flows into the Ebro River. The Cinca River is 170 km long and flows through a rich agricultural region.
Identification

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Typology

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Plan of situation:
3.1.3 Gauging station of Segre:

The Segre River in Catalonia is an important tributary of the Ebro. Its basin covers areas of France, Andorra and Spain. It rises on the Northern side of the Pic del Segre, in Upper Cerdanya, and after running 265 kilometres on its way to Mequinenza, flows into the Lower Cinca. It is comprising three dams, two of which, the Oliana and the Rialb, are within the Consortium area, as are two of its tributaries, the Rialb River and the Ribera Salada.

![Segre gauge station](image)

**Fig. 11: Segre gauge station**

### Identification

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### Typology
3.1.4 Gauging station of Ribarroja:

Ribarroja Dam, is a concrete gravity dam located in the province of Tarragona, Spain, that impounds the Ebro. About 35 km upstream of Ribarroja dam is Mequinenza dam. About 15 km downstream is Flix dam. Ribarroja Dam is a 60 m tall (height above foundation) and 362.4 m long gravity dam with a crest altitude of 76 m. The volume of the dam is 800,000 m³. The dam features a spillway with 7 gates over the dam (maximum discharge 11,670 m³/s) and two bottom outlets with a maximum discharge of 273 (2635) m³/s.
Identification

<table>
<thead>
<tr>
<th>River</th>
<th>Ebro</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiving basin (km²)</td>
<td>85.001</td>
</tr>
<tr>
<td>Exploitation system</td>
<td>UNDER EBRO</td>
</tr>
<tr>
<td>Municipal T.</td>
<td>Ribaroja de Ebro</td>
</tr>
<tr>
<td>Province</td>
<td>Tarragona</td>
</tr>
<tr>
<td>Sheet 1: 50,000</td>
<td>FABARA (443)</td>
</tr>
<tr>
<td>State</td>
<td>high</td>
</tr>
<tr>
<td>Start</td>
<td>1968</td>
</tr>
<tr>
<td>Cota (m)</td>
<td></td>
</tr>
<tr>
<td>Code ROEA</td>
<td>9804</td>
</tr>
<tr>
<td>Code SAIH</td>
<td>E004</td>
</tr>
<tr>
<td>Code SAICA</td>
<td></td>
</tr>
<tr>
<td>UTM X</td>
<td>787,621</td>
</tr>
<tr>
<td>Y</td>
<td>4,571,451</td>
</tr>
<tr>
<td>Spindle</td>
<td>30</td>
</tr>
<tr>
<td>Datum</td>
<td></td>
</tr>
<tr>
<td>Datum</td>
<td>ETRS89</td>
</tr>
</tbody>
</table>

Typology

<table>
<thead>
<tr>
<th>Owner</th>
<th>ENDESA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vol. Reservoir to NMN (hm³)</td>
<td>210</td>
</tr>
<tr>
<td>NMN (m)</td>
<td>70</td>
</tr>
</tbody>
</table>

Plan of situation:  

Section type:
4 Numerical modelling:

A model is defined as a representation of a system or phenomenon in which simplifications have been made in scale and/or time compared to the prototype. In engineered systems, models and their associated simplifications of reality are often created to be able to understand and reproduce to some extent complex physical processes that occur in nature. For example, when studying reservoir systems, being able to predict water movement (hydraulics or hydrodynamics) and sediment movement that will occur in response to a storm or dam operation is useful. The two models most commonly employed for this type of analyses are physical models and mathematical models. Historically, physical models were often employed in reservoir studies along with simple numerical computations. Given the recent advances in computing power, mathematical models are now common either as stand-alone analysis tools or used in conjunction with physical models.

As it was introduced Iber software (Bladé et al., 2014b), which is a tool for numerical simulation of water flow and fluvial processes in rivers and estuaries, is the tool used for this study. Apart from solving the water hydrodynamics, Iber has a series of modules to solve different processes as bedload and suspended sediment dynamics, water quality or hydrological processes. The numerical solver of sediment transport is coupled to the hydrodynamic module.
of Iber, which solves the 2D shallow water equations written in conservative form using the finite volume method and the numerical scheme of Roe (Roe, 1986).

The reader is referred to Bladé et al. (2014b) and the references therein for a detailed description and experimental validation of the numerical schemes used to solve the shallow water equations, which are not included here for the sake of conciseness. This hydraulic module has been applied to several studies in the past, including river inundation modelling (Bladé et al., 2014a), overland flow (Cea and Bladé, 2015), evaluation of gully restoration measures (Castillo et al., 2014), wood transport in rivers (Ruiz-Villanueva et al., 2014) and water quality loss (Bladé et al., 2014a; Cea et al., 2016).

The sediment transport module solves the non-cohesive non-stationary sediment transport equations. They include the bedload transport equations and the suspended sediment transport equations, coupling the bedload and the suspended load through a sedimentation-rise term. The sediment transport module uses the velocity, depth and turbulence fields from the hydrodynamic and turbulence modules. In this work no bedload has been considered. The suspended load transport is modelled from a depth averaged turbulent convection–diffusion equation, as is done for any species in the water quality model as described in detail in (Cea et al., 2016):

\[
\frac{\partial hC}{\partial t} + \frac{\partial hU_x C}{\partial x} + \frac{\partial hU_y C}{\partial y} = \frac{\partial}{\partial x_j} \left( \left( \Gamma + \frac{\nu_t}{S_{ct}} \right) h \frac{\partial C}{\partial x_j} \right) + (E - D) \tag{11}
\]

Where \(C\) is the depth-averaged concentration of suspended solids, \(U_x, U_y\) are the horizontal depth-averaged velocity components, \(\Gamma\) is the turbulent viscosity, \(\Gamma\) is the molecular diffusion coefficient for suspended solids, and \(S_{ct}\) is the Schmidt number, which relates the moment turbulent diffusion coefficient with the suspended turbulent diffusion coefficient, \(D\) is the deposition rate and \(E\) the entrainment rate.

Under the assumption of no bedload, the bed level variation is calculated as:

\[
(1 - p) \frac{\partial Z_b}{\partial t} = D - E \tag{12}
\]

For cohesive soils the linear threshold model firstly proposed by (Partheniades, 1965) and (Ariathurai and Arulanandan, 1978) is used for \(E\). In it, the erosion rate depends on the difference between the shear stress \(\tau_b\) and strength (or erosion critical stress) \(\tau_{ce}\) and a parameter \(M\) representative of the erosion rate (in fact equivalent to an erosion rate when: \(\tau_b = 2 \cdot \tau_{ce}\))
\[ E = M \cdot \left( \frac{\tau_b}{\tau_{ce}} - 1 \right) \] \[ \text{[13]} \]

For D the following widely used expression (Einstein and Krone, 1962), which considers a deposition critical stress \( \tau_{cd} \), is used:

\[ D = \left( 1 - \frac{\tau_b}{\tau_{cd}} \right) \cdot W_s \cdot C_a \] \[ \text{[14]} \]

\( C_a \) is a near-bed concentration assuming the Rouse profile calculated according to (Huybrechts and Villaret, 2010), and \( W_s \) the settling velocity calculated with the Van Rijn formula (Van Rijn, 1987) which is widely used in large scale applications (Duan and Nanda, 2006)

### 4.1 Sediment transport parameters in Ribarroja reservoir

The presented numerical sediment transport module is based on the equations presented in the previous section, these equations by no means are able to represent in detail the whole complexity of the natural sediment dynamics. The calibration process consisted in obtaining a set of values for parameters M, \( \tau_{ce} \), \( \tau_{cd} \) and the sediment diameter \( d \) (which affects the settling velocity \( W_s \)) for a good fit of a calculated accumulated sediment volume curve to that resulting from experimental data.

*Table 1: Fitting parameters, obtained with 2D fine mesh model*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>M (m/s)</td>
<td>6.10 \cdot 10^{-8}</td>
</tr>
<tr>
<td>( \tau_{cd} ) (N/m²)</td>
<td>1.2</td>
</tr>
<tr>
<td>( \tau_{ce} ) (N/m²)</td>
<td>1.1</td>
</tr>
<tr>
<td>d (μm)</td>
<td>34</td>
</tr>
</tbody>
</table>
CHAPTER: III
DATA ANALYSIS

1 Gauging stations data sets

As it was mentioned in the introduction the objective of the data analysis is to obtain the general behaviour along Ribarroja reservoir, for that a yearly hydrograph of each station mentioned in chapter II was made.

The data used in this study was taken from the platform: SAIH EBRO, and the software used for the data analysis was Microsoft Excel.

The data obtained from the platform are ordered by day from October first, 1964 to September 30th, 2015 Fig. 16, and presented missing data, the problem was solved by substituting them by the averaged values or taking out the year presenting a lot of missing data for example the year 2012-2013 was take out from the data set of the gauge station of Mequinenza.

Table 2: Statistical summary of all data collected in (m³ / s)

<table>
<thead>
<tr>
<th>Stations</th>
<th>Mequinenza</th>
<th>Cinca + Segre</th>
<th>Ribarroja</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>229</td>
<td>73</td>
<td>312</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>202</td>
<td>50</td>
<td>202</td>
</tr>
<tr>
<td>Min</td>
<td>12</td>
<td>24</td>
<td>70</td>
</tr>
<tr>
<td>Max</td>
<td>1185</td>
<td>473</td>
<td>1290</td>
</tr>
<tr>
<td>Flood period</td>
<td>Jan - Mar</td>
<td>Mai - Jun</td>
<td>Feb - Mar</td>
</tr>
<tr>
<td>Low discharge period</td>
<td>Jul - Oct</td>
<td>Aug</td>
<td>Aug</td>
</tr>
</tbody>
</table>

As shown in Table 2, the average flow rate in Mequinenza and Ribarroja is around 270 m³/s, a very high flow rate compared with that of Cinca + Segre, which is normal, Mequinenza and Ribarroja are reservoirs whereas Cinca and Segre are small rivers cross-port on Ribarroja what explain the high flow rate in this reservoir. The flood period is usually in winter time and sometimes in spring, while the period of low discharge is in summer in all of stations.

The Fig. 15, shows the raw historical data of the gauging station from 1964 to 2015, all the zero values all along the time line represent the messing data, and the pikes represent the floods
events which occurs usually in winter and spring time. The objective of this data analysis is to obtain
the yearly hydrograph, but the big challenge was to get rid of missing data so they don’t distort the results. In order to solve this problem four approaches were implemented which will be developed in the following section.
Fig. 15: historical data of Mequinenza gauging station from 1964 to 2015


2 Yearly average hydrographs

For a better understanding of sediment transport phenomenon, four different approaches were taken, in order to obtain the yearly average hydrograph

- **Approach 1:** In this approach a yearly hydrograph of each station from 1964 until 2015 was calculated, taking in consideration the minimum and maximum values [Fig. 16].

- **Approach 2:** In this approach a yearly hydrograph of each station from 1964 until 2015 was calculated, taking out the minimum and maximum values. [Fig. 17].

The results obtained were the following hydrograph:

*Mequinenza:*

![Mequinenza Approach 1](image)

*Fig. 16: Yearly hydrograph gauge station: Mequinenza approach 1*
According to Fig. 18 there is no big difference between approach 1 and 2 in term of flow rate, but approach: 2 in term of dispersion is less than approach 1, that’s why approach 2 was chosen.

As this two approaches are obtained by averaging the same dates (day and month) of each year in the historical data set the eventual floods occurred every year in different dates, will reduce
the values of those flood events. Therefore, these two approaches don’t show this sort of flood events that are the responsible of the sediment transport. This idea can be observed in next chapter (chapter 4).

The same method was applied on the other gauge stations.

The rest of gauge stations can be found in the Annex.

This reduction in the values of the flood events described in the previous paragraph will introduce the necessity of improving the yearly averaging in order to obtain a new approach that show these flood events.

- **Approach 3**: In this approach a yearly classified curve of each station from 1964 until 2015 was calculated, taking in consideration the minimum and maximum values Fig. 19

- **Approach 4**: In this approach a yearly classified curve of each station from 1964 until 2015 was calculated, without taking in consideration the minimum and maximum values Fig. 20

The results obtained were the following classified curves:

*Mequinenza:*

![Fig. 19: Yearly classified curve gauge station: Mequinenza approach:3](image-url)
According to figure 23 there is no big difference between approach 3 and 4 in term of flow rate, but approach 4 in term of dispersion is less than approach 1, that’s why approach 4 was chosen.
The same method was applied on the other gauge stations. 

*The rest of gauge stations can be found in the Annex.*

The next step is to reorder the data obtained in the approach 4. This is done by ranking the data obtained from Approach 2 in descending order and taking the days equivalent to the descending order to reorder the data from Approach 4 from October 1 to September 30, and finally obtain the yearly hydrograph, and to compare it to the approach 2, as shown in **Fig. 22**.

The results obtained were the following hydrograph:

---

**Fig. 22:** Steps of reordering the data of approach 4

---

The results obtained were the following hydrograph:
Mequinenza reordered:

![Yearly reordered hydrograph gauge station: Mequinenza, approach:4](image1)

**Fig. 23:** Yearly reordered hydrograph gauge station: Mequinenza, approach:4

![Comparison between Approach 2 and 4, gauge station: Mequinenza](image2)

**Fig. 24:** Comparison between Approach 2 and 4, gauge station: Mequinenza

The **Fig. 24**, emphasize the big difference between approach 2 and approach 4; the fact of averaging the raw data taking out the messing data and minimum and maximum values gives a
general behaviour of the river but the flood events and the periods of shortages are underestimated, a problem that has been solved by approach 4, in particular by classifying the data and averaging the flood periods together and the periods of shortages together, that what explains why in **Fig. 24** in the period from day 1 to day 106 Julian day the equivalent to the first of October and the 14th of January and the period from day 194 to 365 Julian day the equivalent to the 12th of April and the 30th of September the hydrograph of approach 4 present values lower than the hydrograph of Approach 2 and a higher values in the period from day 106 to day 194 Julian day the equivalent to the 14th of January and the 12th of April (winter and spring) this period is known by floods events that we can see in the hydrograph.

The same method was applied on the other gauge stations.

*The rest of gauge stations can be found in the Annex.*
CHAPTER: IV
NUMERICAL MODELING

The main focus of this chapter is to show the results obtained from the simulation using IBER software, which will be divided in two sections: hydraulic and sediment.

Hydraulic:
- Specific discharge (m$^2$/s)
- Bed shear stress (N/m$^2$)
- Depth (m)
- Velocity (m/s)
- Water height (m)

Sediment:
- Erosion (m)
- Suspended sediment discharge (m$^2$/s)
- Suspended sediment concentration (g/l)

Three virtual measurement points (Red, Green, Yellow) on the mesh were picked and also two days were choosing: Julian day 181 and Julian day 348 which correspond to 30 of Mars and 13 of September respectively, and finally a comparison between the rests of approach 2 and 4 was made.

Fig. 25: localisation of the virtual point (Red, Green, Yellow)

1 Comparison of Approach 2 and 4

1.1 Section: Hydraulic
Specific discharge (m²/s)

Fig. 26: Map of specific discharge (m²/s) in Ribarroja Reservoir for Julian day 184 (up) and 348 (down) obtained for approach 2.
Fig. 27: Map of specific discharge (m²/s) in Ribarroja Reservoir for Julian day 184 (up) and 348 (down) obtained for approach 4.
Measurement points:

*Fig. 28: Time evolution of Specific Discharge (m²/s) in the three virtual stations in fig 24 for approach 2 (up) approach 4 (down)*
The graph shown in Fig. 28 are different in term of shape, nevertheless they present some similarities.

- **Similarities:**
  - Both graph present a rise in term of specific discharge during the winter and spring period, this is normal, this is the period of precipitations and the melting of snow.
  - The red and green virtual gauging stations of both approaches behave as river, which normal due to the localisation of the virtual point as shown in Fig. 25.
  - The yellow virtual gauging station of both approaches behave as a basin

- **Differences:**
  - Each graph presents a different specific discharge; a high specific discharge in approach 4, this can be explained as explained previously in chapter III, the way approach 4 was calculated allowed to averaging floods periods and periods of droughts.

Another important point, the fluctuation shown in Fig. 28 (up) yellow virtual point, could be explained by the fact of the opening of the gates of the Mequinenza dam.

**Bed shear stress (N/m²):**
Fig. 29: Map of Bed shear stress (N/m²) in Ribarroja Reservoir for Julian days 184 (up) and 348 (down) obtained for approach 2.
Fig. 30: Map of Bed shear stress (N/m²) in Ribarroja Reservoir for Julian day 184 (up) and 348 (down) obtained for approach 4.

Measurement point:
Fig. 31: Time evolution of Bed shear stress (N/m²) in the three virtual stations in fig 24 for approach 2 (up) approach 4 (down)

Depth (m):
Fig. 32: Map of Depth (m) in Ribarroja Reservoir for Julian day 184 (up) and 348 (down) obtained for approach 2.
Fig. 33: Map of Depth (m) in Ribarroja Reservoir for Julian day 184 (up) and 348 (down) obtained for approach 4.

Measurement point:
Fig. 34: Time evolution of Depth (m) in the three virtual stations in fig 24 for approach 2 (up) approach 4 (down)

The yellow virtual gauging station is the deepest of all the three stations due to its localisation (Ribarroja reservoir).

Depth and Bed shear stress are two parameters inversely proportional; as shown in Fig. 32, Fig. 33 and Fig. 34, the deeper is the water is the lower is the bed shear stress; the winter and spring periods have more rainfall and snowmelt, which means that the water gets deeper, hence less bed shear stress

Velocity (m/s):

![Velocity diagram]
Fig. 35: Map of Velocity (m/s) in Ribarroja Reservoir for Julian day 184 (up) and 348 (down) obtained for approach 2.
Fig. 36: Map of Velocity (m/s) in Ribarroja Reservoir for Julian day 184 (up) and 348 (down) obtained for approach 4.

**Measurement point:**
As shown in Fig. 37, in winter and spring time an increase in terms of velocity appeared in the graph, with a spike of the yellow virtual station at 1.4 (m/s) in the spring and a spike at 1 (m/s) of the red station in the spring, and finally a spike at 0.9 (m/s) of the green station in the winter. The two graphs presented some similarities and some difference:

- **Similarities:**
  - Both graphs piques in the same periods at more or less intensity.
  - The shapes of the of the graphs are more or less the same shapes.

- **Differences:**
  - The major difference the period from day 265 to day 321 equivalent to the 22\textsuperscript{th} of June and 17\textsuperscript{th} of August.

The conclusions made by the comparison of the velocity with the previous parameters are all the parameters are related to each other.

The velocity and the depth, are inversely proportional whereas the velocity and bed shear are proportional; when the velocity piques the bed shear piques too.
**Water height (m):**

*Fig. 33:*

*Fig. 38: Map of water height (m) in Ribarroja Reservoir for Julian day 184 (up) and 348 (down) obtained for approach 2.*
Fig. 39: Map of water height (m) in Ribarroja Reservoir for Julian day 184 (up) and 348 (down) obtained for approach 4.
Measurement point:

**Fig. 40:** *Time evolution of Water height (m) in the three virtual stations in fig 24 for approach 2 (up) approach 4 (down)*
As shown in Fig. 40 as the other parameters, in winter and spring time an increase in terms of water height (m), with a spike of all virtual station at 80 (m). The two graphs presented some similarities and some difference:

- **Similarities:**
  - Both graphs show a bump in the same periods at more or less height.
  - The shapes of the graphs are more or less the same shapes.

- **Differences:**
  - The major difference the period from day 265 to day 321 equivalent to the 22\textsuperscript{th} of June and 17\textsuperscript{th} of August, the shape of the graphs changes.

As mentioned previously all the parameters are related to each other.

### 1.2 Section: Sediment

*Erosion (m)*
Fig. 41: Map of water Erosion (m) in Ribarroja Reservoir for Julian day 184 (up) and 348 (down) obtained for approach 2.
Fig. 42: Map of water Erosion (m) in Ribarroja Reservoir for Julian day 184 (up) and 348 (down) obtained for approach 2.

Measurement point:
The graphs shown in Fig. 43 present some similarities and some differences.

- **Similarities:**
  - The shape of the red and the yellow virtual gauging station in both graph is more or less the same.

- **Differences:**
  - The major difference is the green gauging station in the approach 2 is almost zero in term of (erosion / sedimentation) at the beginning and a little of sedimentation in the spring, whereas in approach 4 is almost 1m of sedimentation.
  - Around day 9 to 17 day 25 in approach 2 virtual stations (red, green) a pique of 10 m of sediment was noticed who is not present in approach 4.

The big differences between the two graphs in Fig. 43, are the consequences of the difference in the way of the calculation of the yearly hydrograph of each approach the was discussed in the previous chapter.

As the flow rate of approach 2 is lower than the one of approach 4, this affected the erosion in the green virtual gauging station, the erosion / sedimentation is almost zero contrary to approach 4 as shown in Fig. 43.
Suspended sediment discharge (m²/s):

Fig. 44: Map of water Suspended Sediment Discharge (m²/s) in Ribarroja Reservoir for Julian day 184 (up) and 348 (down) obtained for approach 2.
Fig. 45: Map of water Suspended Sediment Discharge (m$^3$/s) in Ribarroja Reservoir for Julian day 184 (up) and 348 (down) obtained for approach 4.
Measurement point:

The graphs shown in Fig. 46 present some similarities and some differences.

- **Similarities:**
  - The overall shape of the graphs is more or less the same in the period from day 1 to day 251 the equivalent to the first of October and the 8th of June.
- **Differences:**
  - The virtual gauging station (green and yellow), are inversed from approach 2 and 4 in the period from day 1 to day 251 the equivalent to the first of October and the 8th of June, with different suspended discharge.
  - The shape of the graph in the period from day 251 to day 331 equivalent to the 8th of June and the 27th of August changed completely from approach 2 to approach 4 the suspended sediment discharge is zero in this period in approach 4.

These graphs shapes shown in **Fig. 46**, resemble to the previous graph shape of the previous parameters (velocity and bed shear stress) and inversed in the case of depth.

Once again, the big deference noticed in the period from day 251 and day 331 Julian day the equivalent to the 13th of May and 17th August, between the two graphs of approach 2 and 4 can be explained by the way of the calculation of the yearly hydrograph, as shows **Fig. 24** during this period in approach 4 the flow rate is almost zero, thus the sediment is not moving.

**Suspended Sediment concentration (g/l):**

![Suspended Sediment concentration graph](image-url)
Fig. 47: Map of water Suspended Sediment concentration (g/l) in Ribarroja Reservoir for Julian day 184 (up) and 348 (down) obtained for approach 2.
Fig. 48: Map of water Suspended Sediment concentration (g/l) in Ribarroja Reservoir for Julian day 184 (up) and 348 (down) obtained for approach 4.

Measurement point:
The graphs shown in Fig. 49 present some similarities and some differences.

- **Similarities:**
  - The overall shape of the graphs is more or less the same in the period from day 1 to day 249, equivalent to the first of October and the 6th of June.

- **Differences:**
  - The shape of the graph in the period from day 249 to day 329, equivalent to the 6th of June and the 24th of August, changed completely from approach 2 to approach 4. The suspended sediment discharge is zero in this period in approach 4.

This graph shape shown in Fig. 49 resembles the previous graph shape of the previous parameters (velocity and bed shear stress) and inverted in the case of depth.

The overall conclusion of this analysis of the results of the numerical modelling:
The red and green virtual stations gauging stations act like a river, whereas the yellow one act like a reservoir, this is due to their position in the Ribarroja reservoir Fig. 25.

In terms of sediment: The most of the sediment are present in the yellow station next to the Ribarroja reservoir, and in the area around the green station, this is could explained by the fact that the sediment coming from Cinca and Segre end up in the area around the intersection of Mequinenza and Segre (red virtual gauging station), but the majority of it get quickly pushed out by the flow coming from the Mequinenza dam, while the sediment coming upstream Mequinenza get stuck in the dam, this phenomenon appeared in Fig. 3, where it is visible that the water coming from Mequinenza is clear whereas the one coming is turbid.

The sediment coming from Segre and Cinca now is moving towards the green station where a part of it get stuck in the border of the ‘S’ curve in the area of the green station, depending on the season and velocity and the depth of the water.

The rest of the sediment continue his journey toward Ribarroja dam where he gets stuck in it.

2 Estimation of the amount of sediment stuck in Ribarroja dam

In order to estimate the amount of sediment stuck in Ribarroja dam, three points was choosing in the study area which are the virtual gauging stations (Red, Green and Yellow).
The formula will allow us to estimate the amount of sediment transported along the Ribarroja river:

\[ C_1 \cdot h_1 \cdot B \cdot \frac{L_{1-2}}{2} + C_2 \cdot \frac{h_1 + h_2}{2} \cdot B \cdot \frac{L_{1-2} + L_{2-3}}{2} + C_3 \cdot h_2 \cdot B \cdot L_{2-3} \]

Where:

C1: Is the Suspended Sediment Concentration of station1 (Kg/m3)
C2: Is the Suspended Sediment Concentration of station1 (Kg/m3)
C3: Is the Suspended Sediment Concentration of station1 (Kg/m3)
h1: is the depth between the station 1 and 2 (m)
h2: is the depth between the station 2 and 3 (m)
L1-2: is the distance between the station 1 and 2 (m)
L2-3: is the distance between the station 2 and 3 (m)
B: is the average of the width of the Ribarroja river

Using the Google Earth software, the distance between these points L1-2 and L2-3 was calculated, regarding the constant B, its calculation is an average of measurements of the width made of the Ribarroja river using Google Earth.
Once again, the same conclusions made for the suspended concentration discharge and sedimentation / erosion parameters holds true here.

The results showing that each year 4 metres of sediment will be added in the Ribaroja dam may be inaccurate quantitively, but qualitatively there are accurate, because this is a simplification in order to know the general behaviour. In order to make these results quantitatively accurate: first of all, the mesh used is the simulation should be more advanced than the one used in this study.

Second more than three measurement point are needed to have some precise results at least 100 points.

And finally, a complete data set are needed.
Conclusions

The main objectives for this study was to obtain the yearly hydrograph of Ribarroja reservoir, in order to run a simulation in Iber software, to know the overall behaviour for the river part downstream Mequinenza dam, Cinca and Segre, and also for the reservoir part of Ribarroja, finally estimate the amount of sediment all along this river.

The yearly hydrograph has been calculated according to two different approaches, the first one is averaging all the data set taking out the messing data, the minimum and maximum data, but the flow rate resulting from this approach couldn’t trigger the movement of the sediment. And the second approach is averaging the descending ordered data set and reordering it after the averaging process.

The benefits of this approach are that it preserves the flood events and the results were positive. The main differences of the results from the two approaches, in terms of the sedimentation is, the first approach didn’t show any sedimentation or erosion in some area of the Ribarroja reservoir, but in term of velocity, bed shear stress and specific discharge the results were more or less the same with a slight difference in the periods of water shortage, this is due to the way of calculating the yearly hydrograph of each approach.

The results obtained from this study are not accurate, because the main objective was to obtain a general behaviour of the sediment transport in this area, thus the simplification of the mesh for more accuracy a more advance mesh is needed.

Although the results obtained are not precise they still relevant and should ring the bell of emergency in the ministry responsible for dams and water management in the regions of Catalonia, to take the necessary measures to limit the damage to generate by the mudding of the dam Ribarroja.

And finally, I hope to have the opportunity to work again on this subject in my PhD thesis.
REFERENCES


Annex

Fig. S1: Yearly hydrograph gauge station: Cinca approach:1

Fig. S2: Yearly hydrograph gauge station: Cinca approach:4
Fig. S 3: Comparison between Approach 1 and 2, gauge station: Cinca

Fig. S 4: Yearly classified curve, gauge station: Cinca approach.
**Fig. S 5:** Yearly classified curve gauge station: Cinca approach 4

**Fig. S 6:** Comparison between Approach 3 and 4, gauge station: Cinca
Fig. S 7: Yearly hydrograph gauge station: Segre approach: 1

Fig. S 8: Yearly hydrograph gauge station: Segre, approach: 2
Fig. S 9: Comparison between Approach 1 and 2, gauge station: Segre

Fig. S 10: Yearly classified curve gauge station: Segre approach: 3
Fig. S 11: Yearly classified curve gauge station: Mequinenza approach:4

Fig. S 12: Comparison between Approach 3 and 4, gauge station: Segre
**Fig. S 13:** Yearly reordered hydrograph gauge station: Cinca + Segre, approach: 4

**Fig. S 14:** Comparison between Approach 2 and 4, gauge station: Cinca + Segre
Fig. S 15: Yearly hydrograph gauge station: Ribarroja approach:1

Fig. S 16: Yearly hydrograph gauge station: Ribarroja approach:2
Fig. S 17: Comparison between Approach 1 and 2, gauge station: Ribarroja

Fig. S 18: Yearly classified curve gauge station: Ribarroja approach:3
Fig. S 19: Yearly classified curve gauge station: Ribarroja approach:4

Fig. S 20: Yearly classified curve gauge station: Ribarroja approach:4
Fig. S 21: Yearly reordered hydrograph gauge station: Ribarroja, approach:4

Fig. S 22: Comparison between Approach 2 and 4, gauge station: Ribarroja