Chapter 3

Impacts of River Dams

3.1 Hydrologic impacts

3.1.1 Introduction

Building water works to such an extent is assumed to have an influence on the riverine fluvial system. For most engineering calculations and management decisions the change of mean in yearly maximum discharge has been of greater importance, especially concerning the diverse discussion of the national water management plan which fore-brought the water inter-basin transfer, suggesting the Ebro river as a major water source.

3.1.2 Data basis

For long-term analysis the time-series for the Tortosa gauging station was selected. Data was obtained from the Service for Gauging and Statistics from the Ebro waterboard (Servicio de Aforo y Estadistica). Data processing was done using GNU Octave and Matlab, converting data formats to numerical Julian calendar format and replacing missing values with NaN.

Secondly data was observed for missing time-series values. Original time-series revealed lacking daily data for the years 1935-1951. Several methods were tried to fill the data gap, but it had to be concluded that the data generated was not sufficiently reasonable to be included in any data analysis.

Large reservoirs have been built in 1945, 1960, 1966 and 1974. Therefore the pre-dam phase has been defined up to 1945, whereas the post-dam series starts from 1974. Looking at the raw data it is assumed, that the data is available for the pre-dam phase from 1st of january 1913 until the 31st of october 1935, meaning for nearly 23 hydrologic years. For the post-dam phase data starts from the 1st of november 1975 reaching up to the 30th of september 2002.

From a hydrologic point of view not only the mean river discharge is of importance, but especially the extreme distribution and thus the magnitude and return period of extremal events, like floods for large extremes or draughts for small extremes. Experience values state that the historic discharge time-series at Tortosa and thus the period prior to the Spanish Civil War cannot be used for minimal extremes, due to installation problems. Hence all analysis work undertaken is entirely focused on maximum extreme events.

It was assumed that the time-series obtained from the Ebro water-board website represents a reviewed and clean data-set. In combination with the data available for reservoir construction it was concluded from the Tortosa discharge data-set, that the pre-war discharge data might be seen as pre-dam construction discharge data. In order to compare a pre-dam with a post-dam situation it was being assumed that after 1976 no reservoir volume was added to the basin. Thus a post-dam data-set was generated from the period after 1976. It was assumed that both data-sets are independent so that a distribution fitting may be undertaken. Both data-sets did not contain outliers larger than 3 standard deviations. Subsequently a variety of extreme distributions were fitted to both data-sets using the minimum least squares method. Extreme distributions were taken from the Flood Analysis package available for Matlab from [16]. In order to compare data-sets further, the extreme distribution building the least common denominator for both data-sets was selected, in this case a 2 parameter log-pearson distribution. To find out whether fitted distributions for pre-dam and post-dam data-sets had changed, the distributions were compared using a two-sided Kolmogorov-Smirnov test. Results revealed that applying a 5 per cent confidence limit for the null hypothesis, distributions are not equal. Also the post-dam extreme distribution is smaller. Detailed results can be taken from table 3.2. General statistics can be seen in table 3.1. A graphical illustration of pre-/post-impact differences can be seen in figure 3.1.

3.1.3 Peak Over Threshold Analysis (POT)

These primary results fortified an initial assumption that distribution of extremal events have changed due to reservoir construction. In order to investigate this impression in

Data-set	Minimum	Maximum	Mean	Std.deviation	Skewness
Pre-dam	1560	4990	2717	748	0,33
Post-dam	360	3303	1465	793	0,65

Table 3.1: *Basic statistic parameters for pre-, post-dam data*

Type	Null hypothesis	P-value
Two-sided	Pre-impact mean $\neq$ Post-impact mean	$5.61*10^{-7}$
One-sided	Pre-impact mean $<$ Post-impact mean	$2.81*10^{-7}$
One-sided	Pre-impact mean $>$ Post-impact mean	1

Table 3.2: *Using the discharge data-set from Tortosa gauging station t-tests were applied for the pre-impact phase ranging from 1913 to 1935 and the post-impact series from 1976-2002. Returned P-value represents the likelihood of the acception for values near 1 or rejection for values near 0 of the initial null hypothesis with a 5% confidence limit. Tests conducted can be interpreted the way that neither both data-set means equal nor is the mean from the pre-impact phase smaller. It can be verified that the post-impact series mean is smaller than the one taken from the pre-series.*

more detail it was assumed that a discharge change should relate to reservoir volume represented by cumulative reservoir volume. To automate the process applied to the data-sets it was concluded that rather than looking at extreme events, the excesses should be considered. An excess analysis or also known as peak over threshold (POT) analysis applies a threshold in order to determine excesses. That way changes in distribution parameters over time can be observed only considering the extreme event tail of the distribution [15]. This can be done by applying a general Pareto distribution (GPD). The cumulative GPD can be defined as follows

$$F(x;\xi;\beta) = \begin{cases} (1-\xi\frac{x}{\beta})^{\frac{1}{\xi}} & ,if\ \xi \neq 0 \\ (1-exp\frac{x}{\beta}) & ,if\ \xi = 0 \end{cases} \tag{3.1}$$

In this case β is defined as the scale parameter and ξ as the shape parameter for a distribution as a function of x. The uniqueness of the Pareto distribution is that if x follows a GPD with the above definition, then exceedences over a threshold value u are also distributed as a GPD with $F(x;\xi;\beta-\xi u)$. From [15] the probability density function can be defined as follows:

$$P(X > u+y|X > u) = \frac{(q-\xi\frac{u+y}{\beta})^{\frac{1}{\xi}}}{(q-\xi\frac{u}{\beta})^{\frac{1}{\xi}}} = (1-\xi\frac{y}{\beta-\xi u})^{\frac{1}{\xi}} \tag{3.2}$$

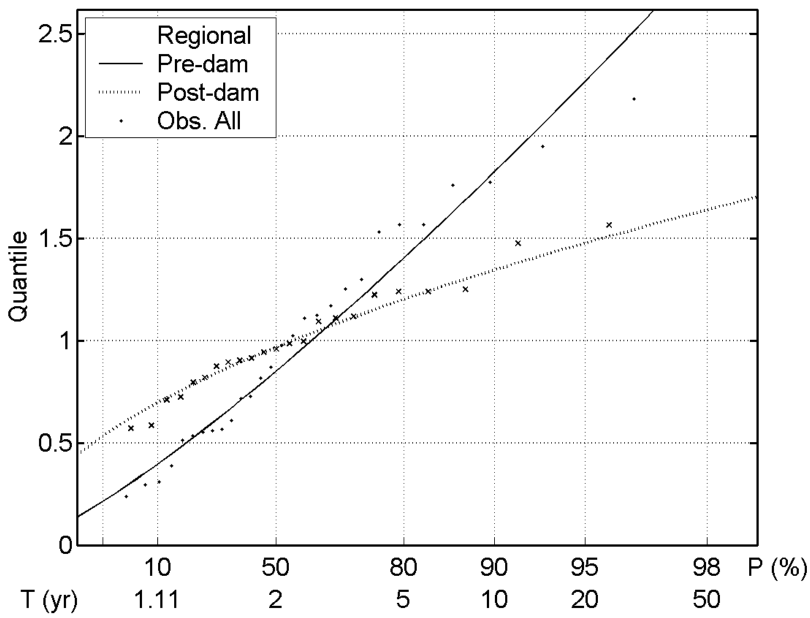

Figure 3.1: *Log-normal distributions with two parameters showed the greatest correlation for pre- and post-impact data-set as the common denominator. Distributions were fitted using the minimum least squares algorithm. Comparing the two distributions evaluated it can be noticed that the post-impact one has larger values up to a return period of about 3 years and flattens more for larger return events.*

As another property of the GPD if $\xi > -1$, then E, the mean exceedance probability over u, is a linear function of u and can be expressed as follows [15]:

$$E(X-u|X>u) = \frac{\beta - \xi u}{1+\xi} \tag{3.3}$$

In practice evaluating the threshold excess value u has not been automated yet. Setting the limit too high will lead to too few data-points and hence a greater uncertainty in distribution fitting, whereas setting the excess value too low may conclude in considering data that does not belong to extreme events. As a general approach setting u in such a way that a quasi-linear relationship for exceedances above threshold values occurs. For the analyzed data-set this may be illustrated as seen in 3.2.

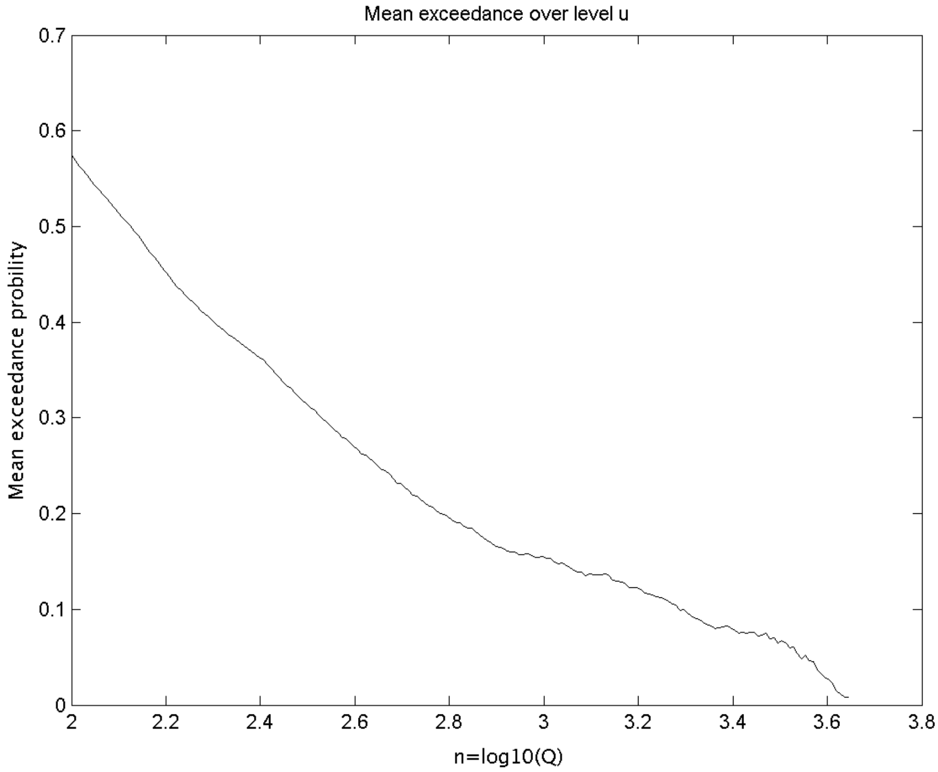

Figure 3.2: *Illustrated is the mean excesses probability for the Tortosa discharge data-set during the period from 1953 to 1979 applying a movable threshold value u, where u is being defined as $log_{10}(m^3/s)$. Note the quasi-linear relation as seen in equation 3.3.*

The POT analysis was undertaken on a log_{10} scale, thus all discharge data was firstly converted. In order to be able to set the threshold value as high as possible and in order to compensate for local effects, a moving window for several hydrological years was established. Practice revealed a time-range of 10 years as a good value. Further it was assumed that a minimum number of excesses had to be gained first in order to have the fitting procedures disposing over sufficient fitting accuracy. Fitting was done using the very complete WAFO toolbox for Matlab which is freely available over the Internet [32]. Testing the available fitting algorithms revealed that between 6 and

10 excess values for each moving window had to be achieved in order for the fitting algorithms of the toolbox to work. The Wafo toolbox disposes over the fitting algorithms moments method, Pichaud's estimation method, the probability weighted method and the minimum least square method. Thus a script was written that determines the maximum threshold value for a given number of excesses for a given period of time. Initially the time-series was defined for the range between 1953 and 1983. It was concluded though that the data from the years 1980 and 1983 decreased the possible threshold value significantly so that the data-series was shortened to consider only the years 1953-1974. For a minimum number of 6 excesses per window during the mentioned period, a threshold value of u_{max}=3,3 (1531,6 m^3/s) was determined. In order to illustrate changes in the Pareto distribution, the fitted parameters where used to calculate inverse values for a probability of 0,9 within the excess range. Determined inverse values from the generalized Pareto probability density function were compared with the cumulative reservoir volume curve as seen in figure 3.3. It can be seen clearly that between 1961-63 the magnitude for x decreases. In return the cumulative reservoir volume increases. Keeping in mind that a $\Delta t = 10$ years moving window is being applied in comparison to the cumulative volume, the year 1963 comprises discharge extreme events between 1963 and 1973. During this period a strong increase in available cumulative reservoir volume occurred, which explains the strong drop in magnitude for a probability of $P = 0,9$. Subsequently no harsh drop can be observed, since the moving window already covers the time-range of flow being affected by reservoir construction. This can be seen as a proof of the initial hypothesis that reservoir construction and its volume has a direct impact on the discharge extreme event distribution. With increasing reservoir capacity available throughout the basin, the extreme event distribution is altered in such a way, that magnitude decreases towards the tail with equal probability. Seen from this point of view, increased reservoir capacity also must be seen as a flood protection measure for downstream areas, although contemporary flood protection policy has changed its measures.

3.1.4 Conclusion

Once underlined the assumption that dam building has had an influence on the downstream river discharge characteristics, techniques applied have allowed to link direct reservoir volume distribution evolution and the evolution of extreme event distribution. Hence with increased reservoir volume the extreme distributions of moving windows have flattened. Thus return values for a given probability have decreased accordingly and it can be concluded that reservoir volume has a flood-dampening effect, possibly dispersing the intensity of the event.

3.2 Ecologic impacts

Ecology research has been fairly sparse in the lower Ebro region, thus a literature review only reveals scattered information. The cited data will not be used for further model evaluation.

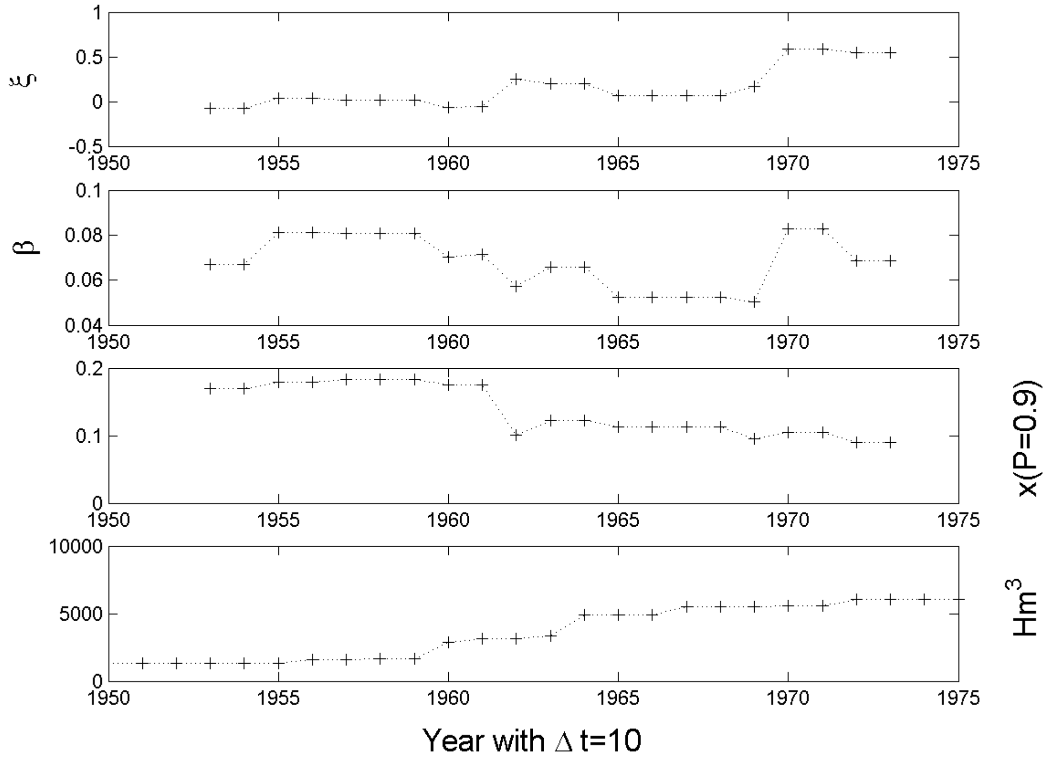

Figure 3.3: *Applying a $\Delta t = 10a$ moving window to excesses of discharge data on a log_{10} scale from the Tortosa station, the shape parameter ξ and the scale parameter β are determined using the minimum least square algorithm from the WAFO toolbox. With evaluated parameters the event magnitude $x(P = 0,9)$ for the probability $P = 0,9$ is calculated using the generalized Pareto probability function. Results are being compared with the cumulative reservoir volume available throughout the Ebro basin. A sharp drop in magnitude x between 1961-63 reflects changes being made to the river system throughout the basin. As the $\Delta t = 10$ years moving average window considers the time-scale up to 1971-73, a sharp drop occurs only once, since during this time-range most volume increase takes place.*

3.2.1 Sedimentology

3.2.1.1 Long-terms changes

Sedimentology has undergone great changes in the Lower Ebro due to river-dam influence. This is known to have a significant impact on the future existence of the Ebro delta, which is under continuous erosion from the Mediterranean sea. First proposals have been made to artificially route sediments from reservoirs into downstream waters, especially at Mequinenza and Flix. Detailed tabular information can be seen in Table 3.3.

Year	Capacity [km^3]	Transport [10^6Mt/year]	Data source
1877	0	30	Gorría (1877)
1944	0,72	22	Unknown
1961-1963	3,45	2,2	Catalàn (1969)
1964	3,45	8,7	Varela et al. (1986)
1976-1982	6,45	0,32	Varela et al. (1986)
1983-1986	6,28	0,15	Palanques (1987)
1986-1987	6,28	0,13	Muñoz (1990)
1988-1990	6,28	0,12	Guillén and Palanques (1992)

Table 3.3: *Historical data on sediment transport in the lower Ebro basin according to [2]. Illustrated is the development of reservoir capacity and sediment transport along time for available data sources. Note the sharp decrese from 1944 to 1961-1963 and 1976-1982 respectively. This decrease is thought to be caused by river dam construction.*

3.2.1.2 Seasonal changes

The reduction in discharge and sediment transport due to dam construction has lead to the suppression of peaks as a consequence to flood regulation. The lastly reported large flood in the lower Ebro was noted in 1937 [2] causing changes in the estuary. A registered extreme event lastly took place in 1907, when a peak of 23484 m^3/s was recorded at Tortosa. Assuming a measured suspended sediment transport concentration of 8,5 g/l [2] at that time and a flood discharge of 20000 m^3/s during one hour, a load of 612Mt/h can be estimated which amounts to 5,1 times the current annual load.

3.2.1.3 Daily changes

According to Ibañez [2] the changes in daily sediment transport cycles are small inspite of changes in discharge. Suspended material transport stays low due to retention in reservoirs with values ranging from 10-20 mg/l [3] [19].

3.2.2 Salinity

3.2.2.1 Long-terms changes

Using the data of mean monthly flows in the decades before the inauguration of the Mequinenza-Ribarroja reservoirs (1960-1970) and comparing them to the data collected afterwards (1970-1980), changes in presence and size of the salt-wedge in the Ebro delta have been estimated [2]. In [2] the mean critical discharge for salt wedge formation is assumed to be equal to the mean annual discharge of each decade (525 m^3/s and 450 m^3/s, respectively) . Results indicate a decrease in the presence of the salt wedge in its position of maximum size respectively intrusion (32 km) and an increase in its medium position (18 km). Detailed information can be taken from table 3.4.

Length (km)	Discharge (m^3/s)	Freq. 1960-1970 (m/yr)	Freq. 1970-1980 (m/yr)
32	$<$100	1	0,1
18	100-300	3,2	4,6
6	300-450	-	3,1
	300-525	2,1	-
0	$>$450	-	4,2
	525	5,2	-

Table 3.4: *Changes in the salt-wedge before and after dam construction [2]. Listed are the durations of occurence or frequency (months/year) at certain discharges of the salt wedge in the lower Ebro. The spatiall distribution is defined by the length upstream from the river mouth. It can be observed that landinwards at 32 km the frequency decreases over time, whereas at 18 km it increases.*

[2] note that there is a linear relationship between discharge and the depth of the freshwater-saltwater interface at any point along the estuary. With known depth along the shallow reaches it should therefore be possible to determine the critical river discharge for the salt-wedge breakup or advancement. However there is evidence of changing depth of the estuary with changing discharge [22].

3.2.2.2 Seasonal changes

Results from [2] investigations conclude that comparing a pre-dam post-dam situation, the salt-wedge has decreased its return period for the maximum extend at 32 km upstream and increased in its medium position at at 18 km upstream. Also they note that there has been an increase in the mean presence of the salt-wedge in the estuary from 6,8 months for the period 1960-1970 in compared to 7,8 months for the period 1970-1980. They lead this back to the decrease in discharge due to the dams' influence. It shall be noted that the presence of the salt-wedge was reported north of Tortosa before the large dams went into operation [21].

In his thesis work [3] recommends for river management the maintenance of flows higher than 100 m^3/s during long periods apart from the summer. This would allow the recolonozation of the fluvial-deltaic zone defined in his work by some species of the riverine benthos. Maintenance of high flows around 400 m^3/s is also recommended in order wash the salt-wedge away and to avoid progressive accumulation of reduced organic matter sediments in the bottom of the fluvial-marine zone.

3.2.2.3 Daily changes

First investigations of daily changes of the salt-wedge have been undertaken by [3]. Conductivity measurements show a sharp de- or incline in respect to the tide. Thus it might be assumed that drastic daily changes due to reservoir building cannot be found.

3.2.3 Water quality

Indicating parameters for water quality have been given by works from [19] investigating the limnologic relationships for the lower Ebro river and its canals. The following parameters have been observed in order to find ecologically related mechanism.

- Temperature
- Conductivity
- pH
- Alkalinity and inorganic carbon
- Oxygen
- Chemically bound nitrogen
- Chemically bound phosphor

[19] undertook a multivariate analysis of parameters mentioned above including the respective discharge. It was found, that temperature and discharge are most significantly related to the other parameters. Alkalinity, nitrates and oxygen follow a positive correlation to the discharge, whereas they are negatively correlated to the temperature. Phosphor is found to relate to temperature. Organic material correlates negatively to oxygen and nitrogen levels. She draws this back to the presence of the salt-wedge in the estuary which tops the accumulated suspended matter and organic matter causing oxygen and nitrate deficits. Correlations are significantly weakened during low-flows.

Biologic parameters were also analyzed. Phytoplancton concentrations depend equally on the discharge and temperature inputs. Low-flows during summer trigger algae populations, whereas high discharges diminish phytoplancton concentrations due to their low residence time. [19] notes that diffusion of seasonal cycles due to reservoir storage has caused elevated nutrient level nitrates and phosphates mentioned especially. This should have caused the increased spreading of algae populations and in increase in effluent eutrophication. She furtherly notes that these conditions enrich the environment with organic material in the form of bacteria and algae, representing 67% of the proteins present, which represent the best form of nutrition for organisms.

3.2.3.1 Long-term changes

[17] has undertaken an analysis of the temperature records from the Ebro observation station located in Roquetes, near Tortosa. The series comprises data ranging from 1894-2002. He concludes that there has been a significant increase in temperature with 0,008 $^\circ$C/yr with an increasing slope starting from 1977 with yearly increase of 0,027 $^\circ$C/yr.

3.2.4 Conclusion

The area in focus represents a complex ecosystem, whose parameter and the occurring interactions have only begun to be investigated recently. The author was not able to find any long-term observations concerning observed changes in river ecology. It is evident that provenly important parameters like sediment transport, salinity and ambient temperature have undergone changes for various reasons, amongst others the construction of river-dams. Most investigations cited in this chapter recommend changes in current river management. Thus it is reasonable to evaluate potential river management decision-supporting tools. Three of the widely used ones will be applied in the following chapters.