



## Some Morphological Aspects and Hydrological Characterization of the Tagus Floods in the Santarém Region, Portugal

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**Abstract.** In Portugal, few studies have been made of the historical floods of the River Tagus (the longest in the Iberian Peninsula). This fact led to the study of the Lower Tagus (Santarém region) using written historical documents, cartographic documents and hydrological data, consisting mainly of water level records. With the support of the historical documents and the analysis of all the maps, it was possible to verify that human intervention has been fundamental in the morphological changes of the Tagus' channel. The river changed from a braided to a single channel with alternate bars. From the hydrological data, return periods for the floods were determined, using the Pearson Type 3 distribution. The selection of the most important floods, from 1855 to 1998, enabled us to build a "flood hazard scale" for this region.

**Key words:** Tagus river, historical floods, flood hazard

### 1. Introduction

The Tagus has been studied by different organisations, governmental (LNEC – National Laboratory of Civil Engineering and INAG – National Water Institute) and private (HP – Portuguese Hydrotechniques), regarding its hydrological aspects.

However, due to the 1755 earthquake, which destroyed almost the entire city of Lisbon and to the great fire, which destroyed Lisbon's National Archive in 1919, records are few. To remedy this, all the available types of documents, from historical ones to newspapers, were collected and examined. Their study has led to a better knowledge of the Tagus' behaviour – past and present.

The Tagus is the longest river in the Iberian Peninsula (1,110 km) and drains an area of 80,630 km<sup>2</sup>, of which 57,770 km<sup>2</sup> are in Spain and 24,860 km<sup>2</sup> in Portugal (Figure 1). The Tagus basin produces 17,670 hm<sup>3</sup> of water, 5,476 hm<sup>3</sup> in Portugal.

From the border down to the Zêzere river confluence (Figure 2), it runs deeply between high slopes in pre-Cambrian, Cambrian and Palaeozoic units. However, south of Tancos (Figure 2), the Tagus changes direction and spreads out strongly

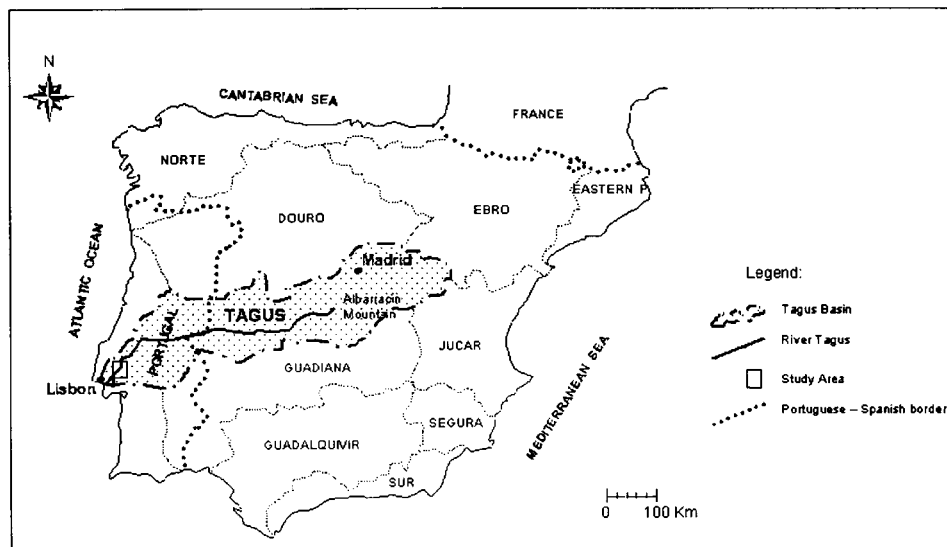


Figure 1. Localization of the Tagus' river hydrographic basin in the Iberian Peninsula.

leading to sediment deposition in an alluvial plain 2 to 10 km wide, which is underlain by soft Cenozoic formations and bounded by Pleistocene terrace sediments. This area, 50 to 100 km North of Lisbon, with approximately 500,000 inhabitants, is classified as an agro-industrial area and it is this area that is most affected by floods. The alluvial plain is where the best Portuguese agriculture soils are: vineyards, fresh fruits and some vegetables are grown. Besides agriculture, cattle, some horses and pigs are also bred. During the biggest floods, some villages can only be reached by boat for several weeks at a time and most roads and railway-lines are cut.

Floods of the Tagus result mainly from long heavy rainfall periods related to the Westerly Zonal Circulation in the North Atlantic. The sub-polar low-pressure and frontal systems, usually occurring at the latitude of the British Isles are, at times of flooding, shifted to lower latitudes (between 40° and 50° N).

The hundreds of reservoirs located in the Tagus basin, influencing the occurrence of floods in the Santarém area (Figure 2), have the total storage capacity of 95% of the streamflow produced by the basin (Daveau, 1995). The Alcântara hydroelectric dam in Spain, near to the frontier with Portugal, with a capacity of 3,333 hm<sup>3</sup>, is particularly critical in this context, in part reflecting the lack of adequate management. This is a delicate problem as the Tagus is an International Basin (Spain and Portugal). The biggest flood of the XXth century (1979 flood) is an example of how this management was inadequate, as both peak floods, from the Alcântara dam in Spain and Castelo do Bode dam in Portugal, met at practically the same time in the Santarém area. Only recently, the two governments have agreed on the adequate management of the dams as well as the coordinated

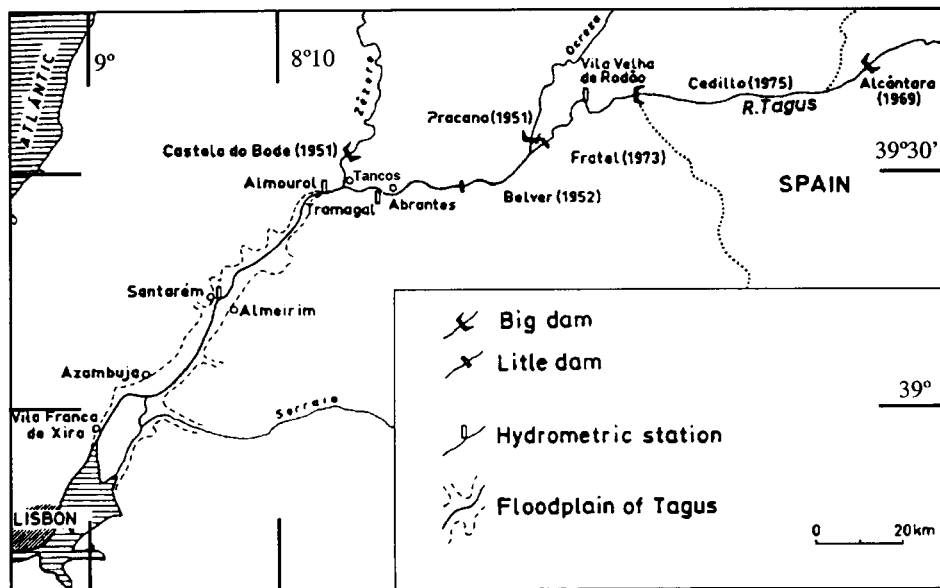


Figure 2. Dams and hydrometric stations along the River Tagus in Portugal; the Tagus' floodplain in the Santarém region is also represented by a dotted line (adapt. Daveau *et al.*, 1978).

management of water resources, in both countries ("Convention on the Cooperation for the Water Protection and Sustainable Usage of the Portuguese–Spanish Hydrographic Basins", signed in 1998). Nowadays, this problem has been mostly surpassed because no discharges are made in Spain without prior communication to Portugal.

For the present study three sources of information were used: written historical documents, old and recent maps and hydrological data, with the purpose of understanding the dynamics of the Tagus that leads to its morphological changes.

## 2. Analysis of Written Historical Documents

An intense bibliographic study on the Tagus and its floods was done in various archives, such as: National Historical Archives of Torre do Tombo, National Portuguese Library, churches, municipal archives, history books and newspapers.

The research of the historical record shows that the channel of the Tagus has been displaced, modified, and reduced in its width by anthropogenic activity, since the Neolithic, as evidenced in many manuscripts, both in Spain and in Portugal. All the works were associated with the needs of man, sometimes to prevent flood catastrophes but mostly to try to make the river navigable and to enlarge the agricultural lands of the owners. Amongst other examples, the latter was done, at times, by drying the area occupied by marshes, thus reducing it (Serrão, 1977; Mattoso 1993; Custódio, 1993).

Major channels of the river were displaced artificially during the reigns of several kings. The most notorious occurred during the reign of D. João III (XVIth century), where a 10 km long channel was moved 1 km northwards from Tancos to Chamusca (Figure 3), in order to stop the silting up of Crown territory by the sands. This measure intended, on the one hand, to stop the destruction of the agricultural lands by the fluvial erosion during floods and, on the other hand, the deposition of sterile sands harmful to agricultural soils (crevasse splay deposits), causing great economic loss (Antologia Nacional da Torre do Tombo, 1750; Dias, 1984; Azevêdo and Nunes, 2000b; Azevêdo, 2001).

River changes also occurred as Portuguese and Spanish kings tried to make the river navigable. In the XVIth century, during the Spanish occupation, navigation was made possible from Lisbon to Toledo (in Spain), after much hard work, including the need for blasting, to destroy all the obstacles in the way.

More recently, in XIXth century, Brigadier Guerra changed definitively the typology of the river by accomplishing great engineering works, such as the construction of dikes, ditches and small-size dams, in order to weaken the flood flow energy.

During all this time, deforestation in the Tagus basin has led to continuous silting up of the riverbed and to the development of the thick sand bodies found throughout the river. The impact of the dams from the middle of the XXth century onwards led to a reduction of the source area supplying the sediment, located downstream from the Alcântara dam, near the Spanish – Portuguese border, and in Portugal, downstream from Castelo do Bode dam (on the right margin of Tagus) and the Montargil and Maranhão dams (on the left margin) (Figure 2). This continuous silting in the lower Tagus, due mainly to anthropogenic activity, diminished in the second half of the XXth century (Quintela *et al.*, 1982). This decrease of sediment input is owing to three main reasons: (a) reduction of the source area (as stated above); (b) reduction of the frequency of the floods, mainly the autumn ones because of the dams retention capacity, which is bigger after the dry summer period; (c) the extraction of fluvial sands of the minor river bed, mainly during the last two decades of the XXth century, which is nowadays about 2,000,000 m<sup>3</sup>/year (Ministério do Ambiente/Instituto Nacional da Água, 2000), mostly downstream of Santarém.

### 3. Cartographic Analysis

Besides all the historical information taken from a variety of archives to fill the gap of missing hydrological data, a detailed cartographic analysis was made, by comparing all the available topographic and geological maps of the area that exist since 1792 to the present, ranging from scales 1/20,000 to 1/200,000 (Nunes *et al.*, 2000; Nunes, 2001). The maps were compared two by two in the same scale. River course, channel morphology, width variations and bar migration were studied and compared over time.

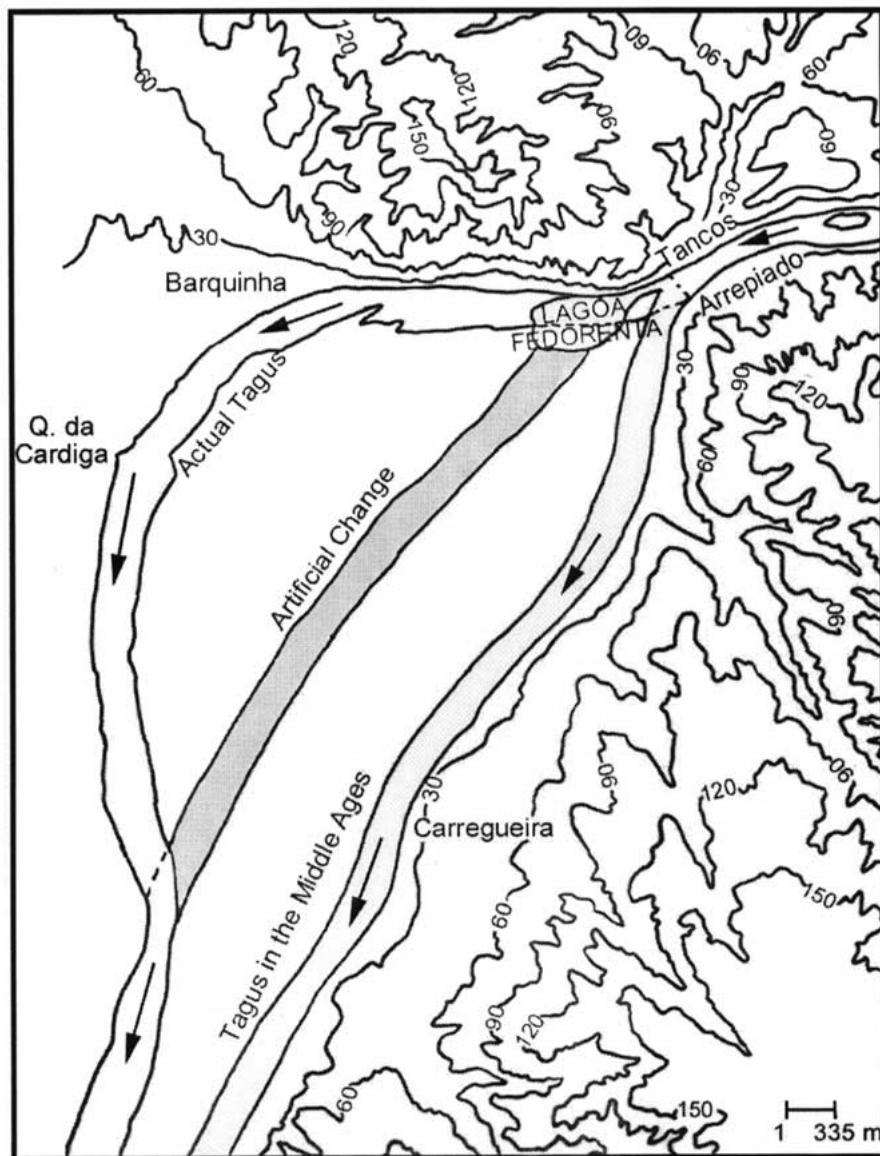


Figure 3. Changes of the Tagus channel, north of Santarém during the XIIIth century (adapt. Dias, 1984).

This study, together with all the available historic references, make it clear that the Tagus was originally a braided river of low sinuosity, with multiple channels separated by large bars. As the Tagus had frequent flood episodes, the river either returned to its former channel or followed a completely different one, with lateral migration occurring across its large alluvial plain.

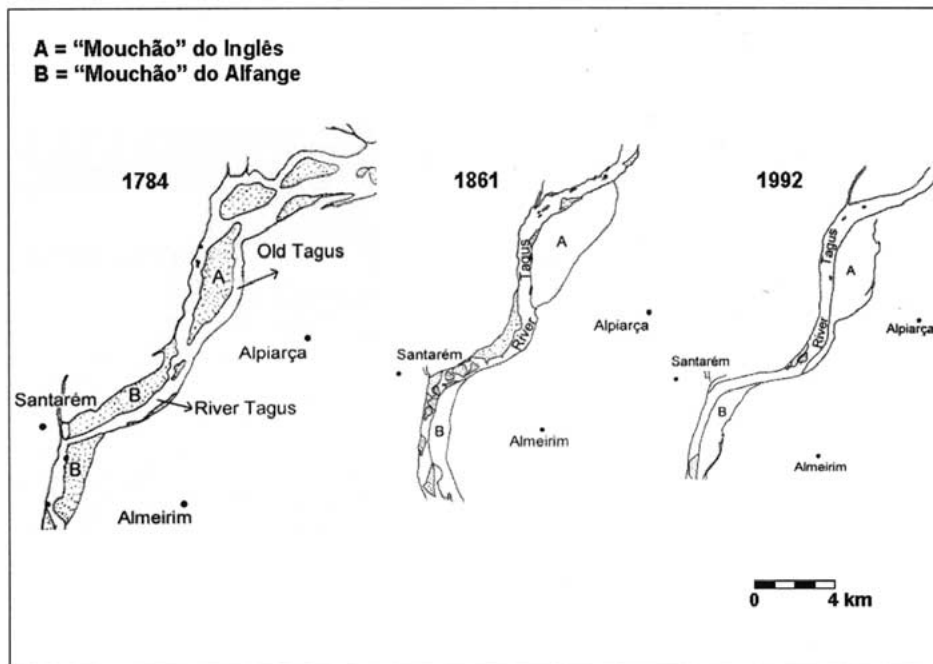


Figure 4. Morphological changes of the River Tagus during the last centuries, in the Santarém region.

This braided character was still visible during the XVIIIth century (Figure 4). However, the river has mainly been losing these characteristics since the second half of the XIXth century, at the time of Guerra's regularization works (Guerra, 1861). This slow evolution in the morphology of the river results mainly from anthropic causes, primarily: (1) the artificial "gluing" of the extensive bars (called "mouchões"), which can reach up to 1 km<sup>2</sup>, to the marginal lands. This normal practice of the owners to enlarge their agricultural lands was the origin of the "acrescidos" (growth of lands by bounding them to the bars). This practice was officially restricted only at the end of the XIXth century. In this way, secondary channels were progressively filled; (2) Guerra's regularization works, which included the construction of dykes, small dams, opening of artificial ditches, removal of sands and straightening of the river channel; (3) the dam's impact, from the 50's on, on the sediments' supply.

Before the influence of the dams and the intense extraction of fluvial sands (during the natural river regime) it was possible to verify that the migration of the sand bars (Figure 5) was in the order of 0.5 m/decade.

Nowadays, the lower Tagus can be considered a low sinuosity ( $s = 1.08$ ) single channel river with alternate bars. When flooding occurs, its flow always returns to the only channel.

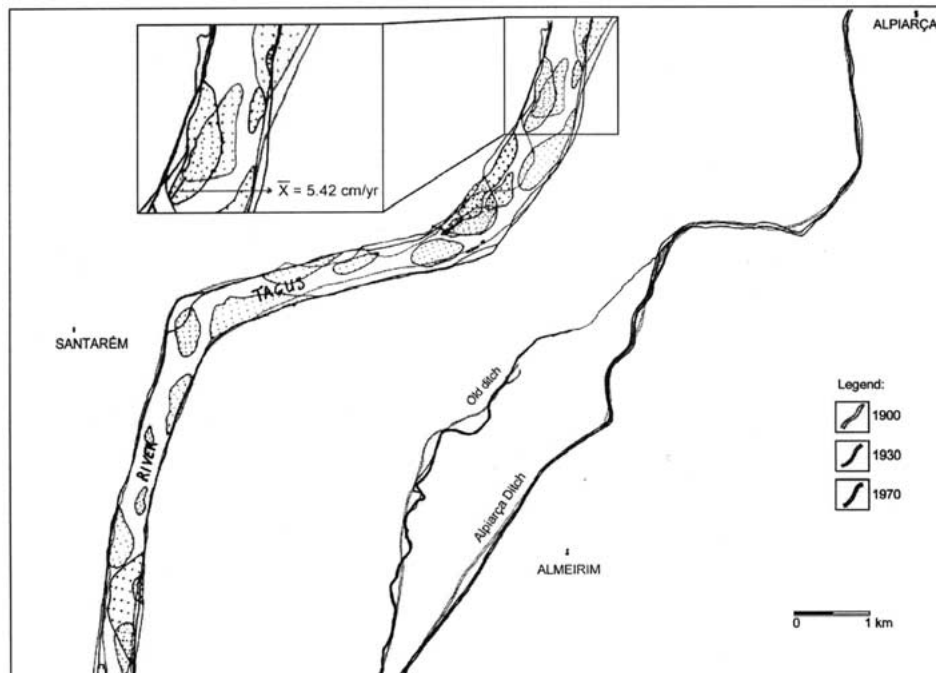


Figure 5. Bar migration, between 1900 and 1970, in the Santarém region.

#### 4. Hydrological Analysis

The non-existence of long continuous series of data, mainly flood discharge values, as well as gauging stations operating in non-simultaneous periods has made the task of developing the study of the Tagus' historic and present floods, burdensome.

Hydrological heights are used because the existing discharge values for the Ponte de Santarém hydrometric station are unreliable, mainly due to the morphological characteristics of the region and of the riverbed itself. As this region is characterized by a very wide alluvial plain (2–10 km in width), it is often difficult to calibrate the heights with the effective discharges, even though the river's discharge-rating curve for this gauging station is known. This implies that it is not easy to quantify precisely the discharges. Because we intend to zone and determine the probability of flooding in each section, the use of heights, which are more reliable, is used.

Many probability distribution models have been proposed and used for the prediction of flood discharges, however, there is no unanimity as to the model to be utilised. In Portugal, and for the particular case of the Lower Tagus Basin (LTB), the Pearson Type 3 distribution is the one that is most applicable to the prediction of floods. The Gumbel Type 1 extreme value distribution (perhaps the most used statistical method in Portugal) must not be applied as a flood prediction model as its adjustment is rejected by an excessive high number of maximum annual

instantaneous discharge series (Henriques, 1985). Then again, we must bear in mind, as explained before, that the use of maximum annual heights instead of discharges is due to the morphological characteristics of the LTB and to the intricacy of calibrating the heights with the effective discharges, as it is difficult to quantify with precision these discharges.

In our study, a non-parametric Mann-Kendall test was applied to the data in order to detect the possible existence of some obliterated trend (Hensel and Hirsch, 1992). This is one of the most frequently applied statistical tests in hydrology, to detect the presence of trends. The advantages of using a non-parametric test in this case are: it is a robust test, not influenced by the presence of anomalous and erroneous values, it can be applied on data of limited accuracy, and it is resistant to the presence of gaps in the data. It can also be adapted to the seasonal behaviour of hydrological variables, as in the present case.

The available data for the Santarém region, collected over a discontinuous period of 150 years (from 1850 to 2000) in several archives (National Water Institute, National Civil Engineering Laboratory), enabled us to calculate the return period of hydrological heights through a series of 71 consecutive years (1922–1991), using the Pearson Type 3 distribution (Figure 6a, Table I). When using the Gumbel Distribution, we verified that it is not suitable for the Portuguese case, as Henriques (1985) already specified (Figure 6b).

Knowing that the big floods of the Tagus submerge almost all the alluvial plain when the waters surpass the height of 7 m (Almeida D'Eça, *in* Sobrinho, 1980), we can verify from Table I that these have a very small return period (2.5 years).

For the biggest flood of the XXth century (1979;  $H = 8.89$  m), a return period of approximately 210 years (Figure 6a) was determined. It occurred after 15 days of rainfall and flooded an area of 871 km<sup>2</sup>. On the other hand, by plotting on the same graph the height of the biggest flood that occurred in the XIXth century (1876,  $H = 8.28$  m; Figure 6a), it shows that its return period is approximately 18 years. Other authors (LNEC – National Civil Engineering Laboratory, 1980), using the Pearson-Foster III Law (empirical method), found a return period of 222 years for the 1979 flood. It must be emphasized that the 1876 flood (well before the building of dams in the Tagus Basin) happened under natural conditions, the waters reaching greater heights in Vila Velha do Ródão (upstream where the river is deeply incised; Figure 2) than in Santarém owing to the morphology of the region. The 1979 flood resulted from continuous non-coordinated discharges from both the Alcântara (Spain) and Castelo do Bode (Portugal) dams.

The application of the Mann-Kendall test ( $Z = -0.213$ ) shows that there is no significative trend in the evolution of the annual maximum hydrological height values, before and after the construction of the reservoirs/dams, as the critical value of 1.96 for a level of significance of 5% is not exceeded. Thus, the artificialization of the river's regime does not seem to have interfered with the annual flood peaks and the flooded area.



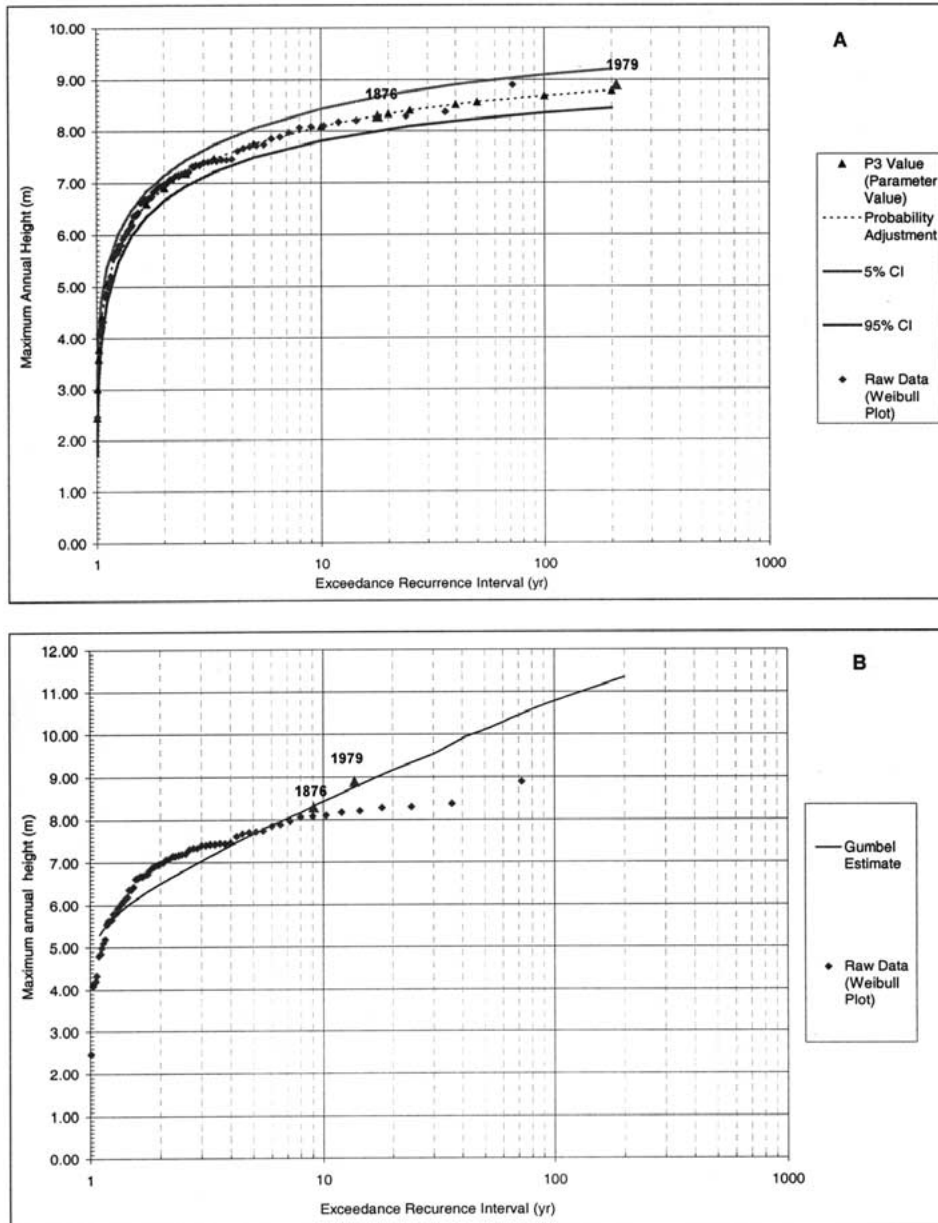


Figure 6. Tagus River flood return periods in the Santarém region, using (A) Pearson Type 3 distribution and (B) Gumbel distribution.

Table I. Pearson type 3 distribution – duration frequency characteristics

P3 value (parameter value)	M (rank)	Probability	Recurrence interval
8.78	1	0.005	200
8.68	2	0.010	100
8.56	3	0.020	50
8.51	4	0.025	40
8.40	5	0.040	25
8.33	6	0.050	20
8.09	7	0.100	10
7.75	8	0.200	5
7.46	9	0.300	3.33
7.18	10	0.400	2.50
6.90	11	0.500	2.00
6.59	12	0.600	1.67
6.23	13	0.700	1.43
5.76	14	0.800	1.25
5.05	15	0.900	1.11
4.40	16	0.950	1.05
4.20	17	0.960	1.04
3.78	18	0.975	1.03
3.59	19	0.980	1.02
3.01	20	0.990	1.01
2.44	21	0.995	1.00

## 5. Definition of a Flood Hazard Degree Scale

Based on the study of written historical records and available hydrological data, the most important floods and direct consequences were compiled, ranging in period, from 1855 to 1998 (Nunes *et al.*, 1999, 2000; Azevedo and Nunes, 2000a). The aim of this work was to try defining a flood hazard degree scale for the Lower Tagus Basin.

The construction of the flood hazard scale took into account six parameters, corresponding to human, agricultural and life supporting impacts, classified from the least (1) to the most hazardous (6). The least hazardous correspond to events that are common during the floods and which the population is used to; the latter are exceptional events. These parameters were pondered, by multiplying by two, from the lowest (2) to the highest (12). The values obtained (from 2 to 42) were grouped into four classes according to a dispersion diagram, as the following:

Classes	Hazard degree	
<12	Low	I
12–24	Medium	II
25–39	High	III
>40	Very High	IV

The low hazard degree (I) contemplates only submersion of roads and railway lines as well as losses of the agricultural production. When there are human casualties, the hazard degrees range from high (III) to very high (IV), the latter comprising all the six parameters (Table II). This Table shows that 42% of the Tagus big floods lead to the loss of human lives and only about 1/5 correspond to a very high hazard degree (IV). All floods in the Lower Tagus are progressive and not of the flash flood type, therefore not so dangerous.

## 6. Conclusions

The analysis of written and cartographic records allowed us to study the behaviour of the Tagus River from 1784 until 1992. Comparing the variations of its channels, namely its course, width and bar migration it was verified that the initial braided character of the river disappeared over time presenting nowadays a single channel with alternate bars. This fact is due to human intervention in the river channel, especially to the “acrescidos” (filling up of the secondary channels in order to enlarge the agricultural lands) and to the regularization works in the XIXth century (removal of sands and straightening of the river channel).

On the other hand, the available hydrological data (maximum annual heights) from 1922 to 1991, allowed us to calculate the return periods for the Santarém region. From these calculations, it was verified that floods over 7 m high (that cover almost all of the floodplain) have a very small return period (2.5 years) and that the biggest flood of the XXth century (8.89 m) attained a return period of 210 years. These 71 years comprise two distinct phases of the river’s regime: the natural (before the 50’s) and the post dam construction. However, as the Mann–Kendall test shows, there is no significant trend in the evolution of the annual maximum hydrological height values.

Finally, the selection of the most important floods between 1855 and 1998, permitted to build a flood hazard scale, which shows that the majority (58%) do not cause human casualties, but agricultural and life supporting systems’ losses. As the progression of the floods is well known and usually slow, in this region, there is time to evacuate the most endangered places and take into action the protection measures.

Table II. Flood hazard degrees in the Santarém Region (Lower Tagus Basin)

Month/Year	Human impacts		Agricultural impacts		Life supporting impacts		Flood hazard scale	
	Deaths	Dislodged people <sup>1</sup>	Lost cattle	Lost agriculture <sup>2</sup>	Communication means blocked <sup>3</sup>	Delivery incapacity of supplies <sup>4</sup>	Weighted value	Hazard degree
	12	8	8	4	2	10		
02-1855			X	X	X	X	24	II
10-1855		X	X	X	X		20	II
01-1856		X		X	X	X	22	II
12-1876			X	X	X	X	24	II
02-1881		X		X	X		12	II
02-1895						X	2	I
02-1900						X	2	I
02-1904				X	X		6	I
10-1907				X	X		6	I
11-1907				X	X		6	I
12-1909	X	X	X	X	X	X	34	IV
12-1910					X		2	I
02-1912	X	X	X	X	X	X	42	IV
04-1916				X	X		6	I
04-1924				X	X		6	I
09-1932				X	X		4	I
02-1936		X	X	X	X		30	III
01-1940		X	X	X	X	X	30	IV
01-1941	X	X	X		X	X	34	III
02-1941	X	X		X	X	X	34	III
03-1947	X	X		X	X	X	34	III
03-1959			X	X	X		6	I

Table II. Continued

Month/Year	Human impacts		Agricultural impacts		Life supporting impacts		Flood hazard scale	
	Deaths	Dislodged people <sup>1</sup>	Lost cattle	Lost agriculture <sup>2</sup>	Communication means blocked <sup>3</sup>	Delivery incapacity of supplies <sup>4</sup>	Weighted value	Hazard degree
11-1967	X	X	X	X	X	X	42	IV
03-1978				X	X		6	I
02-1979	X	X	X	X	X	X	42	IV
03-1979		X	X	X	X	X	30	III
01-1982				X			4	I
11-1983		X	X	X	X	X	30	III
12-1989	X	X	X	X	X	X	42	IV
12-1995		X		X	X	X	22	II
11-1997	X	X	X	X	X	X	42	IV

<sup>1</sup> People left homeless due to the flooding (partial or total destruction) of their houses.

<sup>2</sup> Partial or total destruction of agriculture.

<sup>3</sup> Main roads and railway lines flooded, and destruction (partial or total) of protection dykes.

<sup>4</sup> Supplies (food, water and sources of energy) unable to be delivered to isolated villages and towns.

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