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Evaluation of environmental impacts resulting from river regulation works: A case study from Portugal

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ABSTRACT: Modifications observed on the hydraulic regime of river systems caused by engineering works led to growing awareness of the impacts caused by these engineering constructions. The need to harmonize and integrate both the hydraulic and the ecological/environmental components has been growing, namely in Portugal. This paper presents the work of a multidisciplinary team that carried out, from 1998 to 2003, an evaluation of the ecological impacts of realignment and construction works implemented at the lower part of Mondego river, in central Portugal, in the 80's. The hydraulic and hydrologic alterations in Mondego river, caused by regularization works, have been analyzed and quantified. The main conclusions of the study are that the changes in the Mondego river geometry induced more homogeneous physical and hydraulic conditions and reduced life diversity. However, the construction of a set of transversal groynes, and discontinuities of the bottom elevation, had an opposite effect. Similar conclusions are reported in the literature.

1 INTRODUCTION

1.1 *River corridors and anthropogenic modifications*

It is very important that rivers are approached to as components of a system that include its bordering and connected environment as well. The understanding of the ecological value of river corridors has been gradually assimilated in the last decades, after observations of the serious damages caused in the past by straight engineering interventions, namely, channelization and changes in rivers cross-section geometry. Modifications on the hydraulic regime of river systems cannot be isolated from the total system that comprehends the river basin, groundwater and the supported ecosystems (e.g.: Brooks, 1988).

Presently it is well known that river biological diversity and productivity are a result of habitat diversity and ecological connections. They are kept and balanced by the dynamic river processes of erosion and deposition which, in turn, depend on the water course hydrologic and sedimentation regimes (Brooks, 1988). Therefore, alterations on any of these physical processes, or a loss of connectivity between any of the three spatial borders of a river, may lead to serious changes on the aquatic communities.

In addition to the spatial variables, a forth temporal variable needs to be taken into account, and it is within these four dimensions that any river system must be comprehensively evaluated and managed (Ward, 1989).

The ecological impacts of dam and diversion channels construction, channelization and changes in the river cross-section geometry, may be synthesized as follows:

i. Significant reduction of habitats diversity, since hydraulic works interfere with the natural continuity of the river physical borders, and make more homogeneous both the river bed and the flooded areas.
ii. Reduction in the native species diversity, caused by the disappearance of the species that depend on seasonal flow differences, and spatial habitat variations to survive. Simultaneously, the exotic species

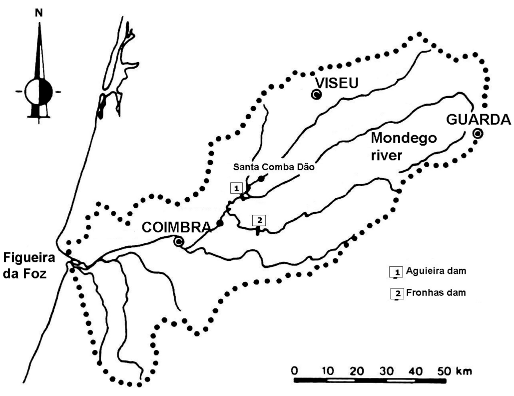

Figure 1. Mondego river basin.

gain a competitive advantage due to the before mentioned alterations.

1.2 *Project framework*

The need to harmonize and integrate both the hydraulic and the ecological/environmental components has been growing since the last four decades. In the past, in Portugal there was a weak connection between such fields of knowledge that today are known to be interdependent.

This paper presents the work of a multidisciplinary team, from two universities (UTAD and ISA) and a state laboratory (LNEC) that carried out, from 1998 to 2003, a study financed by the Portuguese Foundation for Science and Technology. The objectives of the project were to evaluate and quantify ecological impacts of realignment and construction works implemented in rivers. The selected case study was the lower part of Mondego river, in central Portugal (Figure 1), that has been channelized as part of a large river regulation scheme implemented in the 80's.

The study permitted an understanding of the modifications provoked by the river channelization on the local ecosystem. The report by Barbosa *et al.* (2005) presents the study in detail.

1.3 *Study methodology*

The study has been split in different components, being each of the three institutions involved responsible for a sector, as follows:

i) LNEC, in charge of the Project coordination, was responsible for the description of the case study history, including the engineering interventions implement in the Mondego river. The hydraulic and hydrologic alterations caused by the referred to regularization works, have been analysed and quantified by the LNEC team.
ii) LNEC made a literature review in order to synthesize the impacts of river training works, and the concepts of river channelization, restoration and rehabilitation. The aim was to emphasize the need to understand rivers as elements of complex catchment's system that combines surface, subsurface and underground water, quantitative and qualitative variables, all in dynamic interaction, and that are a support to the local ecosystem. The UTAD team put into perspective the importance of biomonitoring results as indicators of the impacts of river regularization works.
iii) The ISA research team was responsible for studying the responses of river plants to channelization, and the effects of habitat disturbance in the ecosystem's invasibility. A comparative study of floral features was conducted among sites in the channelized segment of the Mondego river, and in the near-natural river reaches upstream Coimbra. General differences in plant species composition, distribution and relationship with environment were investigated, with particular attention paid to shifts in richness and cover of native species assemblages, and in the dominance of exotic species (as defined per Richardson *et al.*, 2000).
iv) The study of macroinvertebrate and ichthyic communities of the regulated fluvial ecosystem of Mondego river has been the responsibility of the UTAD team.

In order to find out how the hydraulic works in the lower Mondego river affected the aquatic communities (fish and invertebrates) field work campaigns were implemented during June and September of 2000 and 2001. Fauna was sampled and registered and water quality parameters were measured both in the field and in the laboratory.

2 CASE STUDY – MONDEGO RIVER TRAINING AND CHANNEL IMPROVEMENT

2.1 *General description*

The Mondego river is the largest entirely Portuguese river with a catchment area of approximately 6644 km^2. It originates at an elevation of 1547 m in "Estrela" Mountains and flows through a very narrow valley till Coimbra town, where the valley spreads to form a vast alluvial plain, the Lower Mondego region, which consists of 15000 hectares of land with high agricultural aptitude. The river reaches the Atlantic Ocean near the town of Figueira da Foz (Figure 1).

The hydrological regime of the Mondego river is very irregular, with discharges that can be less than 1 m^3/s during several days in a year, and flood discharges up to 3000 m^3/s (natural situation, before river basin interventions). The average annual rainfall is 1124 mm. The river presents torrential

Figure 2. Flooding in the lower Mondego river.

Figure 3. Mondego river: trained main channel.

characteristics due to the precipitation regime and the strong slopes of the river basin.

Along several centuries, the lower part of Mondego river basin was subject to periodic flooding and many attempts to regulate and channelize the river were performed. The construction of a new river bed downstream Coimbra, at late XVIII century, was kept functional along the years but was judged to be insufficient by mid-XX century due to the erosion of the upper part the river basin and the resulting silting and sanding up of the river and the marginal fields, which caused more frequent flooding of the agricultural lands (Figure 2).

2.2 *River training and flood protection works*

In order to attenuate the annual flood effects (inundation of river banks) thus increasing the agricultural potential of the downstream flood plains, and protect the population, a large river regulation project was implemented in the 80's. This project implied the construction of three large dams: Aguieira, Raiva and Fronhas to control the flood discharges, and a significant training of the river in the lower, flat area of its basin, with the opening of adequately designed channel flanked by unsubmergible embankments, in a distance of about 36 km.

In the design of alluvial bed river training the main objective was to define a dinamically stable channel, i. e., a channel with movable bed where the sediment transport capacity is equal to the equilibrium value.

The main channel (Figure 3) was designed for the modified 100-year flood of 1200 m^3/s (at Coimbra) associated with the 25-year flood of the Lower Mondego tributaries. The bankfull cross sectional geometry is of trapezoidal type. The bottom width varies between 88.0 m and 142.2 m and the maximum depth is 6.5 m. To maintain the desired cross section, the channel banks are protected by riprap with mean diameter of 0.15 mm.

The levees along the main channel have lateral fuse-plug weirs, to permit controlled flooding for discharges higher than the design ones.

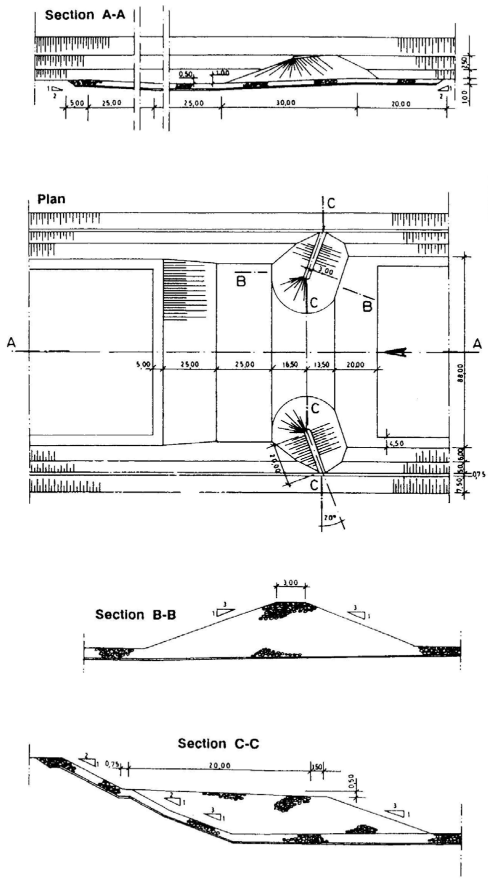

Figure 4. Mondego river groynes. Plan and sections (Lemos *et al.*, 1991).

The Lower Mondego river training project included, within an extension of 11873 m downstream Coimbra town, the construction of a set of groyne-type structures, placed in pairs, and combined with discontinuities of the bottom elevation (Figure 4). Groynes have 20.0 m length and an angle to the flow direction of 70°. Upstream and downstream from each groyne, the channel bed is protected by riprap to prevent streambank erosion.

3 HYDROLOGIC AND HYDRAULIC CONSIDERATIONS

The flow regime of the lower Mondego channelized river reflects the variability of the climate and the physiographic conditions in the river basin and the type of operation of Aguieira, Raiva, Fronhas and Coimbra reservoirs. These reservoirs are part of the Mondego river regulation scheme and are associated with a diversity of water uses (e.g. urban supply, agriculture, industry, energy production). In general, the operation of reservoirs causes changes in either total flow volume or annual distribution of the flow, or both, and in the frequency and magnitude of floods.

To characterize the hydrologic modifications occurred in Mondego river due to the interventions in the river basin two measuring stations were considered: Ponte Santa Clara and Coimbra dam, near Coimbra town. These stations represent the integrated runoff of 74% of the entire Mondego basin and are located immediately upstream the channelized reach of the river.

Historical data from Ponte Santa Clara station between 1939/1940 and 1979/1980 (41 years) was used to analyse the river flow regime before the interventions. This station was discontinued after the construction of Coimbra dam. On the other hand, the period of 1986/1987 to 2003/2004 (18 years) was considered as representative of the present situation (Barbosa *et al*., 2005), after an analysis of the number and size of reservoirs and the date of their construction.

Based on the analysis of the mean daily flows and flood hydrographs some modifications on Mondego flow regime have been identified:

– The average total runoff is 2424 hm^3. This value reflects a slight reduction (14%) in the total runoff due to water diversion for agricultural, urban and industrial supply.
– Although river flows maintain a marked seasonal pattern, there has been a reduction of the monthly mean discharges, between February and June, and an increase of the low flows between July and September. The mean monthly discharges may vary between 16 m^3/s and 205 m^3/s. The flow duration curve presents a more gentle decline, without long periods of zero streamflow, as occurred in natural conditions.
– Aguieira and Fronhas reservoirs ensure the regulation of 80% of the river basin upstream Coimbra town. For approximately 20 consecutive years these reservoirs managed to control the river flood discharges and no inundation of the agriculture fields was registered. However recent flood events (January 27, 2001) have demonstrated that high peak discharges can occur due to the contribution of the many Mondego tributaries. In this event, the maximum flood discharge reached 2000 m^3/s exceeding the design value of the river Mondego main channel, leading to levee failure and extensive flooding of the marginal fields. The flood water remained on the plain for several days destroying many farms and causing severe damages to agriculture.

Concerning the hydraulic conditions on the Mondego river, no information on the trained river bed evolution was available during the present study. However, due to human activities upstream Coimbra dam, namely sand mining, and the construction and operation of Aguieira and Fronhas dams, it is sup-posed that a reduction on the sediment transport had lead to a degradation of the trained mobile river bed.

Accordingly with the work of Belo and Cardoso (1993) significant bed degradation was observed since 1977, in a 33.2 km reach of river Mondego up-stream Coimbra town due to the aforementioned activities.

4 RESPONSES OF RIVER PLANTS TO CHANNELIZATION EFFECTS OF HABITAT DISTURBANCE IN THE ECOSYSTEM'S INVASIBILITY

4.1 *Sampling procedures*

Fito-ecological surveys were carried out in May–June 1999 at six sites placed at regular intervals along the channelized segment and at three sites in the "natural" river. Three longitudinal transects of five 5 × 25 m plots were laid out at each studied site. The first transect was positioned instream and in the waterlogged margin, while the others were placed on each of the two-stage terraces, whilst the "natural" transects were located in the corresponding areas of the fluvial corridor – i.e. the in-stream and waterlogged margins, inner-bank and outer-banks. The richness and percentage of foliar cover in each plot were visually estimated for each exotic and native species by averaging the results from 2.5 × 2.5 m sub-plots ($n = 10$ in each plot). Environmental variables that potentially influence the vegetation establishment were estimated for each plot (e.g. substrate, distance from the water) or measured (e.g. conductivity). Site-specific variables were also achieved (e.g. river corridor width).

4.2 *Data treatment*

A correspondence analysis was carried out, so as to evaluate channelization effects by comparing plant species composition and distribution in 'natural' and channelized plots. The number and foliar cover of native and exotic species were also compared, using non-parametric Mann-Whitney U tests. Data from plots of the channelized river segment were subjected to a canonical correspondence analysis and to a classification using the unweighted pair-group arithmetic average clustering.

4.3 *Results and discussion*

Exotic plant species in fluvial ecosystems are known to be associated with human-disturbance and its establishment and invasive spread frequently conduct to an over-turning of native species assemblages (Hood & Naiman, 2000).

In this study, significant differences in the distribution and vegetation features (richness and cover) were observed, however the number of plant species recorded was very similar, with 150 species present in the 'natural' corridor, 160 species on the channelized part, and 98 were common to both. A small number of exotic species was recorded (around 10% of the total flora), which was coupled with low exotic species richness found per plot (maximum 8 species, average 2.8). However, exotic species were dominant in some plots, especially in the channelized river. *Eryngium pandanifolium*, a swamp-dwelling plant from the South-American subtropical zone, dominated the instream plots and the first terrace at downstream sites, but was substituted by another exotic species, the knotgrass (*Paspalum distichum*) at the upstream ones. The exotic hydrophytes *Azolla filiculoides* and the parrot feather (*Myriophyllum aquaticum)* were also largely disseminated in instream plots. Below the riparian woody vegetation, in shady and wet habitats, dense stands of the South-American species *Tradescantia fluminensis* were established. On the second terrace the increase in exotic cover was due mainly to the presence of the silver wattle (*Acacia dealbata*), a woody Australian species. Knotgrass, silver wattle and *T. fluminensis* were also found at the 'natural' sites, but with the exception of the latter on the inner bank, consistently had a lower degree of cover. Figure 5 presents the comparison of native and exotic species cover between the "natural" and channelized river segments, at the three transects.

Aguiar *et al.* (2001) pointed out two potential reasons for the channelized river's higher susceptibility to exotic invasion. Firstly, the strong disturbance of the physical environment caused by the channelization, regulation and expansion of the irrigation area led to new and favorable environmental conditions to invasion, including a reduction in the intensity and frequency of scouring floods and an increase in the fine sediment and nutrient load. Secondly, the synergistic effect of higher propagule pressure and the successful dispersal capability of the exotic species that were already present.

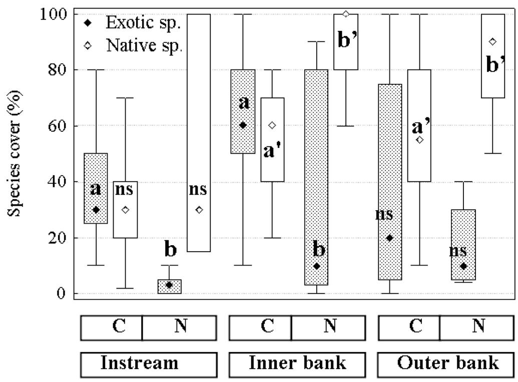

Figure 5. Comparison of species cover for exotic and native species between the channelized (C) and the "natural" (N) river at the three transects. Median (black or white lozenge), non-outlier range, and 25%, 75% percentiles are represented. Columns with different letters indicate significant differences at $p < 0.05$, using Mann-Whitney U tests for comparison tests, within each group of species (a′, b′ for native species, and a, b for exotic species; ns = non-significant test). Note that inner bank and outer bank corresponds to 1st terrace and 2nd terrace for the channelized segments, respectively.

The riparian woody species have rapidly recovered after the channelization project, and the structure and composition of the riparian woody layer of the first terrace, is rather similar with the riparian gallery of the "natural" river, however overstorey herbaceous species had a varying composition, whilst the vegetation of the 2nd terrace clearly diverges in species composition from the "natural" area. This experimental evidence can be related with the loss of interactive pathways, which are maintained in non-impacted floodplain rivers, namely the vertical and lateral connectivity with the river channel (Ward & Stanford, 1995). In the channelized segment of Mondego river, the first terrace is located 2 m above the water, and the original river connections were preserved, but the second terrace, which is positioned 4 m above the water, led to the likely disruption of vertical and lateral interactions with the river channel.

Figure 6 presents the canonical correspondence analysis biplot of the channelized segment data (sites from 1 to 6, with 1 being the site closer to the estuary and 6 the most upstream site), with the selected variables obtained by a forward selection procedure. The first axis clearly represented a transverse gradient of moisture (water→terraces), whereas the second axis displayed the longitudinal gradient of the river (upstream→downstream). Conductivity and channel depth were also aligned with the distance

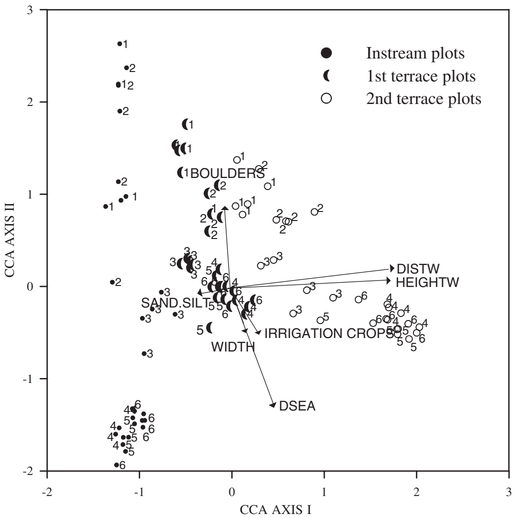

Figure 6. Axis one and two of the canonical correspondence analysis biplot using the floral composition of the channelized Mondego segment. Numbers indicate sites (each site with five plots per transect). Substrate: BOULDERS – boulders (%); SAND.SILT – sand and silt (%); WIDTH – channel width (m); DSEA – distance to the sea (km); DISTW – distance of the plot to the water (m); HEIGTHW – height of the plot above water (m); IRRIGATION CROPS – land use on the site surroundings: irrigation crops and rice fields (adapted from Aguiar *et al*., 2001).

from the sea, channel width and irrigated cropland. Site 3, approximately in the middle of the channelized river is a transitional zone in terms of species composition.

Differences in species composition within and along the channelized segment can be observed, regardless of the same engineering procedures and materials used in the channelization process. This suggests the development of microtopographic variations and habitat patches that influenced vegetation establishment, associated with differences in adjacent land-use along the impacted river, and the diverse existing species pool.

5 STUDY OF MACROINVERTEBRATE AND ICHTHYIC COMMUNITIES OF THE REGULATED MONDEGO RIVER FLUVIAL ECOSYSTEM

5.1 *Sampling sites*

Three sampling sites were set in the regularized central bed of the Mondego river (M2, M3, M4), between Coimbra and the river mouth (Figueira da Foz), and

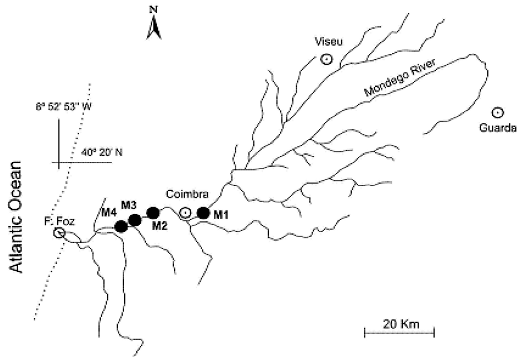

Figure 7. Location of the sampling sites within the Mondego basin. M1 – Reference site; M2, M3 and M4 – Sites on channelized sector.

one located approximately 14 km upstream of Coimbra (M1) – (Figure 7). This last one, was a control site since it was not affected by channelization, although it is located approximately 20 km downstream of the Aguieira Dam. This site has well developed riparian vegetation on the left bank. In contrast, the right bank presents scarce vegetation due to its clear cutting and to the high deposition of materials (small stones, gravel and sand).

The sites in the artificial segment exhibit extensive riprap along the banks, with constant slope of 45°, partially colonized by shrubs and trees (mainly *Populus* spp.). Medium fraction materials (stones and gravel) dominated the riverbed, but were replaced by a lower grain size fraction in the second part of the study after the flood events of 2001. M2 showed a semi-disaggregated groyne with resulting shear stress in the wet channel. A more detailed description of the different characteristics of each meso-habitat is in Table 1. Macroinvertebrate (M) and fish (F) sampling was carried out simultaneously in June (the 6th) and September (the 9th), of 2000 and 2001. Physical and chemical parameters (dissolved oxygen, pH, temperature, conductivity, alkalinity and total suspended solids) were also analysed at the sampling sites during the same periods (Table 2).

5.2 *Benthic macroinvertebrates communities*

Benthic invertebrates were collected from reaches of approximately 100 m in length during a fixed time of 5 minutes (CPUE) by disturbing the substratum upstream of the net using a vigorous kicking and/or feet action. The sampling was performed using a 350 μm mesh net with 600 cm^2 aperture and embraced all the existent biotopes, with an effort proportional to the relative importance of each habitat

Table 1. Characterization of habitats in each sampled site and aquatic communities that were inventoried in each sector: F – fishes; M – macroinvertebrates. Example: M1006 means reference site (M1) sampled in 2000 (second and third code's cypher) in June (fourth code's cypher). The last code refers to habitat type: D- right bank; E- left bank; T- groynes; R- nets; N- riprap; I- sand bank.

Habitat	Mean depth (m)	Dominant substrate	Current ($m\ s^{1}$)	Bank structure	Communities
M1006D	1.20	Stones	0,28	Natural, smooth profile with tree clumps.	F; M
M1009D	1.20		0.28	Natural, smooth profile with tree clumps.	F; M
M1009E	2.50		0.28	Natural with a vertical profile. Riparian vegetation without interruptions.	F
M1016D	1.20		0.28	Natural, smooth profile with tree clumps.	F; M
M1016E	2.50		0.28	Natural with a vertical profile. Riparian vegetation without interruptions.	F
M1019D	1.20		0.28	Natural, smooth profile with tree clumps.	F; M
M1019E	2.50		0.28	Natural with a vertical profile. Riparian vegetation without interruptions.	F
M2006E	0.50	Gravel	0.20	Artificial embankment. 45° slope. Dense riparian vegetation.	F; M
M2006T	0.40	Stones	0.84	Semi-disaggregated submersed weir with stone blocks.	F
M2006R	2.5	Gravel	1.05		F
M2009T	0.40	Stones	0.84	Semi-disaggregated submersed weir with stone blocks.	F
M2009E	0.50	Gravel	0.20	Artificial embankment. 45° slope. Dense riparian vegetation.	F; M
M2016E	0.50	Gravel	0.20	Artificial embankment. 45° slope. Dense riparian vegetation.	F; M
M2016T	0.40	Stones	0.84	Semi-disaggregated submersed weir with stone blocks.	F
M2016R	2.5	Gravel	0.95		F
M2019E	0.50	Gravel	0.20	Artificial embankment. 45° slope. Dense riparian vegetation.	F; M
M2019T	0.40	Stones	0.84	Semi-disaggregated submersed weir with stone blocks.	F
M2019R	2.5	Gravel	1.02		F
M3006D	1.20	Stones	0.15	Artificial embankment. 45° slope. Riparian vegetation with interruptions.	F
M3006N	0.60	Stones	0.25	Rip rap with stone blocks.	F
M3006R	2.0	Gravel	0.55		F
M3009D	1.20	Stones	0.15	Artificial embankment. 45° slope. Riparian vegetation with interruptions.	F; M
M3009N	0.60	Stones	0.25	Rip rap with stone blocks.	F
M3016D	1.20	Stones	0.15	Artificial embankment. 45° slope. Riparian vegetation with interruptions.	F; M
M3016N	0.60	Stones	0.25	Rip rap with stone blocks.	F
M3016R	2.0	Gravel	0.49		F
M3019D	1.20	Stones	0.15	Artificial embankment. 45° slope. Riparian vegetation with interruptions.	F; M
M3019N	0.60	Stones	0.25	Rip rap with stone blocks.	F
M3019R	2.0	Gravel	0.54		F
M4006E	0.70	Sand	0.06	Sand bank with herbaceous vegetation.	F; M
M4006I	1.00	Sand	0.10	Stabilized sand bank with herbaceous and shrubby vegetation.	F
M4006D	1.50	Stones	0.06	Artificial embankment. Riparian vegetation with interruptions.	F
M4006R	2.5	Sand	0.10		F
M4009D	1.50	Stones	0.06	Artificial embankment. Riparian vegetation with interruptions.	F
M4009E	0.70	Sand	0.06	Sand bank with herbaceous vegetation.	F; M
M4009I	1.00	Sand	0.10	Banco de areia estabilizado com vegetaçœo herbácea	F
M4016D	1.50	Stones	0.06	Artificial embankment. Riparian vegetation with interruptions.	F
M4016E	0.70	Sand	0.06	Sand bank with herbaceous vegetation.	F; M
M4016R	2.5	Sand	0.15		F
M4019D	1.50	Stones	0.06	Artificial embankment. Riparian vegetation with interruptions.	F
M4019I	1.00	Sand	0.10	Sand bank with herbaceous vegetation.	F
M4019E	0.70	Sand	0.06	Sand bank with herbaceous vegetation.	F; M
M4019R	2.5	Sand	0.16		F

(Table 1). The nets were washed carefully between collections. The contents of the hand-net were placed in labeled containers, transported to the laboratory, and the specimens sorted alive. 70% ethanol was used for preservation before subsequent identification. Wherever possible, identification was done to species level using the available keys (except Diptera and Oligochaeta).

Table 2. Physical and chemical values at the 4 sampling sites in June/September 2000 and 2001.

Sampling site	D.O. ($mg.L^{-1}$)	pH	Temp (°C)	Cond ($\mu S.cm^{-1}$)	Alkalinity ($mg.L^{-1}$ $CaCO_3$)	TSS ($mg.L^{-1}$)
M1006	9.5	6.5	18.6	76.1	11.8	3
M1009	8.4	7.0	20.6	78.2	14.4	1
M1016	10.2	6.3	22.8	76.3	13.8	3
M1019	9.0	6.5	22.4	79.8	9.3	0
M2006	8.9	6.7	21.1	120.1	22.9	5
M2009	9.1	7.6	23.4	103.0	20.5	1
M2016	6.7	6.4	22.1	128.9	26.4	8
M2019	7.0	7.0	22.3	113.0	18.3	8
M3006	8.6	7.4	25.5	123.5	24.8	8
M3009	10.2	7.7	24.3	149.0	27.7	2
M3016	10.4	8.1	29.0	136.7	31.9	8
M3019	9.6	7.3	25.0	120.9	19.8	5
M4006	9.2	6.9	23.9	149.0	31.8	7
M4009	6.6	6.6	22.4	137.0	35.4	2
M4016	10.4	8.1	24.9	161.0	40.1	20
M4019	7.9	7.2	23.8	129.0	20.9	20

5.3 *Ichthyic communities*

In contrast with benthic collections, fish sampling allowed the discrimination between habitat types in order to detect the influence of hydraulic structures and erosion sedimentation processes (Table 1). Fish were captured using na Electrocatch apparatus, model WFC7-HV, powered by a generator (Honda GX160) of 4.0 KW. Electrofishing used DC current and the voltage was set between 150 to 200 V in order to produce a current from 2.5 to 4 A. This fact, together with a constant capture effort of 7 minutes in each meso-habitat (CPUE), allowed comparable results among the different inventoried habitat types. Electrofishing captures were complemented by 30 × 2.5 m static multimesh gill net (mesh types: 32 mm, 43 mm, 50 mm, 65 mm and 85 mm), which was placed in the deeper pools for 3–4 hours.

5.4 *Data treatment*

To compare sites and periods for both sampled communities, the total number of individuals and Shannon diversity index were computed through PRIMER 5.2.2 (Clarke & Gorley, 2001). Multivariate methods were used to detect the spatial and temporal patterns underlying the biotic and abiotic data. Metric Dimensional Analysis (MDS) was used through the package SYN-TAX 2000 (Podani, 2001) and non-Metric Dimensional Analysis (n-MDS) through PRIMER 5.2.2 (Clarke & Gorley, 2001). N-MDS operated on a sample similarity matrix of the Bray-Curtis coefficient instead of the original data matrix, converting the similarity values to rank order (in order to preserve the original relationships between samples). MDS is a related technique, in the sense that it also uses a distance or dissimilarity matrix but, on the contrary, it assumes the existence of linear relationships between variables. The data files were not transformed to enhance the effect of the density variation of organisms among sites.

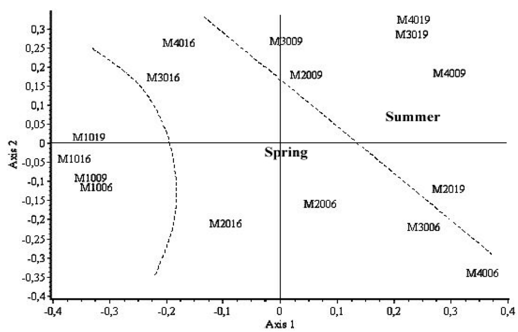

Figure 8. MDS ordination of sampling sites based on benthic invertebrates. Example: M1006 means reference site (M1) sampled in 2000 (second and third code's cypher) in June (last code's cypher).

5.5 *Results*

5.5.1 *Macroinvertebrates communities*

The differences between the reference site and the channelized sector, and the potential effects of the floods in the macroinvertebrate communities were assessed through MDS ordinations of sampling sites. Figure 8 shows a clear separation of the reference

Figure 9. n-MDS ordination of sampling sites based on benthic fauna. In each site was overlapped one circle with proportional radius at relative importance of the sand on the substrate. Abbreviations of the sampling sites are given in Figure 7.

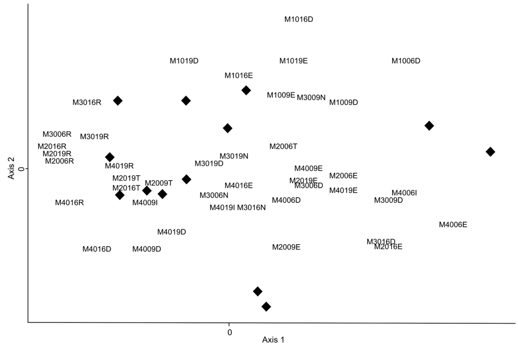

Figure 10. MDS ordination of sampling sites and habitats based on ichthyic communities. Symbols represent fish species. Abbreviations of the sampling sites are given in Figure 7. The last code refers to habitat type (D – right bank, E – left bank, T – groynes, N – riprap, R – nets and I – sand bank).

site (M1) relative to the channelized ones. This site presents, a specific benthic assemblage, characterized by different caddisflies (*Polycentropus* sp., *Plectrocnemia* sp., *Tinodes waeneri*) and stoneflies (*Leuctra fusca*) taxa. On the contrary, some Heteroptera (*e.g. Gerris lateralis* and *Micronecta* sp.) show a preference for the modified sector.

A clear seasonal separation of the sampling sites is another important aspect displayed in Figure 8.

This fact demonstrates the high capacity of recovery of the system since inter-annual differences are obscured by seasonal ones. The importance of riverbed materials in explaining the dynamics of benthic assemblages is illustrated by Figure 9. Here, we can link these changes to the winter peak flows, which cause an extensive deposition of fine sediments, especially clear in site M2. The reduced *stress* value obtained by the n-MDS ordination (0.08) demonstrates a good representation of the global variance.

In the reference site the diversity of benthic organisms was, in general, superior when compared to the channelized sites before the flood events. After this phenomenon, diversity decreased in the reference site, while the total number of individuals did not suffer strong variations. However, in the channelized sites (M2, M3 and M4), the extreme flows were probably responsible for the drastic reduction in invertebrate abundances. Nevertheless, the diversity was not substantially changed in these sites.

5.5.2 *Ichthyic communities*

A total of thirteen *taxa*, six of which were Cyprinidae, were recorded. This family, besides barbel (*Barbus bocagei*), includes three Iberian endemisms (Iberian nase – *Chondrostoma polylepis*, Portuguese roach – *Ch. macrolepidotus*, chub – . *Squalius carolitertii*), and two introduced species (goldfish – *Carassius auratus* and gudgeon – *Gobio gobio*). *Cobitis paludica* was also recorded. Aside from these, two other exotic species were recorded: eastern mosquitofish (*Gambusia holbrooki*), and the centrarchid pumpkinseed (*Lepomis gibbosus*). The migratory diadromous fish species identified were the anadromous sea lamprey (*Petromyzon marinus*), the twaite shad (*Alosa fallax*), the catadromous European eel (*Anguilla anguilla*), and the thinlip mullet (*Liza ramada*).

The influence of floods and channelization on the abundance and diversity of ichthyic communities was not conclusive. However, Figure 10 suggests that the two types of sites (channelized *versus* non-channelized) support different communities. In fact, *Ch. macrolepidotus*, *Gobio gobio* and *Squalius carolitertii* are more represented in the reference site, whereas *B. bocagei* and *Ch. polylepis* are common in both sectors (channelized/non-channelized). The other species (including the exotic ones) are restricted to the artificial segment of the Mondego. The fish populations were discriminated by the meso-habitat in each station, which is also represented in Figure 10. A lack of inter-annual differences may be concluded from this observations, demonstrating a high resilience of fish populations to extreme hydrological events.

It is also possible to see from Figure 10 that a higher number of species exhibit preferences for the meso-habitats T and N (groyne and riprap, respectively). Similarly, a higher density of the majority of species is observed precisely in these habitats.

5.6 *Discussion*

The entire new channel created in the Lower Mondego, after dredging and re-sectioning the old one, and transforming the natural banks in extensive dykes covered by riprap, affected the heterogeneity of habitats with repercussions on different fish and benthic composition, and had a detrimental effect on species diversity (Ward & Stanford, 1983; Cortes *et al*., 2002). The lack of intolerant species (with high oxygen and low levels of nutrient requirements) in artificialized sectors was replaced by benthic communities with short life cycles which can be explained by the reduction of available or suitable habitat, especially when the channel reflects hydro-geomorphic changes as pointed out by Maitland (1990) and Erskine *et al*. (1999).

Infrequent events, which are regarded as being catastrophic because of their immediate effects on ecosystems or on human activity, are capable of leaving long-lasting traces. In this respect they can affect the organization and composition of the patchwork. In spite of resulting from strong disturbances, flood "scars" generally heal quickly; major floods do not disturb the structure and functioning of the patchwork (Bravard & Gilvear, 1996). The most impressive aspect of the effects of floods on aquatic insects is not the devastation of the fauna that occurs, but rather the remarkable ability of species to recover from such severe perturbations (Ward, 1992). The floods that occurred in the winter of 2000/2001 caused substantial alterations in the fluvial dynamics. The increased transport of solid material originated a strong sedimentation of unstable fine materials, leading to a biological impoverishment and alterations in the functioning of the system. Macroinvertebrate communities underwent a substantial reduction of abundance, with larger incidence in channelized sectors, where sedimentation was higher. Nevertheless, despite the floods, macroinvertebrate communities displayed a high resilience, as obtained by Ortega *et al*. (1991) after a flood in the basin of River Segura (Spain). Macroinvertebrates respond to spatial and temporal variability by changes in the structure of their communities. They show tremendous diversity in their life history patterns, including variation in life cycle length, developmental strategies, and seasonality of the various life history stages (Greenwood & Richardot-Coulet, 1996). Such traits explain also the seasonal variations, which were very clear in the Lower Mondego, probably because in changing environments there is a dominance of short-lived species (Hershey & Lamberti, 1998). Ichthyic communities did not show clear inter-annual or seasonal differences. Moreover, the natural hydrological disturbances seemed to produce a low impact. Roux & Copp (1996) argue that the importance of hydrological variation is necessary to complete the biological cycles and that only frequent flow peaks disrupt these communities.

6 CONCLUSIONS

It is generally known that channelization of river courses leads to a decrease in microhabitats. Therefore mitigation structures providing habitat heterogeneity must be installed immediately after channelization (Brookes, 1988; Armitage, 1995).

This study evaluated the environmental impacts resulting from regularization of the Lower Mondego river, in central Portugal. It has demonstrated the impacts of human-disturbance in the vegetation establishment at the channelized segment, with the generalized increase of exotic species richness and cover, and a native displacement of herbaceous vegetation, diverging from the riparian woody species, which has shown a high resilience to intense, but discontinuous habitat alterations.

Concerning the macroinvertebrates it was observed a clear separation between the reference site and the channelized sectors. For instance, some Heteroptera showed a preference for the modified sector. The role of channelization on the abundance and diversity of the ichthyic communities was not conclusive.

The main conclusions concerning the case study are that most of the changes in the Mondego river geometry induced more homogeneous physical and hydraulic conditions and reduced life diversity. However, the construction of a set of transversal groynes and discontinuities of the bottom elevation had an opposite effect. These results are similar to findings reported in the literature, for instance Brookes (1988) and Torre (2001).

For this particular case Vieira & Ferreira (1997) and Silva-Santos *et al*. (2004) argue that the use of groynes and riprap in the Lower Mondego was environmentally positive. All these mitigation structures in channelized reaches increase the heterogeneity of available habitats for the aquatic communities and have been applied to restore streams all over Europe (Nijland & Cals, 2000).

The study also confirmed that biomonitoring over time is a precious tool for integrated river management.

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