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Hydrologic and land-use change influence landscape diversity in the Ebro River (NE Spain)

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Abstract

The landscape dynamics (1927–2003) of one reach at the Middle Ebro River (NE Spain) was examined using aerial pictures and GIS techniques. Moreover, changes in the natural flow regime and anthropic activities within the river-floodplain system were investigated. Our results indicate that hydrological and landscape patterns have been dramatically changed during the last century as a consequence of human alteration of the fluvial dynamics within the studied reach, as well as the overall basin. The magnitude and variability of river discharge events have decreased, especially since 1981, and flood protection structures have disrupted the river floodplain connectivity. As a result, the succesional pathways of riparian ecotopes have been heavily modified because natural rejuvenation no longer takes place, resulting in decreased landscape diversity. It is apparent from these data that floodplain restoration must be incorporated as a significant factor into river management plans if a more natural functioning wants to be retrieved. The ecotope structure and dynamics of the 1927–1957 should be adopted as the guiding image, whereas hydrologic and landscape (dykes, raised surfaces) patters should be considered. Under the current socio-economic context, the more realistic option seems to create a dynamic river corridor reallocating dykes and lowering floodplain heights. The extent of this river corridor should adapt to the restored flow regime, although periodic economic investments could be an option if the desired self-sustained dynamism is not reached.

1 Introduction

Linking landscape patterns and ecological processes is a common goal of landscape ecology (Forman and Godron, 1986). Landscape ecology holds the potential for developing a truly holistic perspective of river corridors by integrating structure, dynamics and function (Ward et al., 2002). The diversity of landscape units and their spatial distributions in pristine riverine landscapes are the result of geomorphological and biological processes and interactions operating across a wide range of spatio-temporal scales. As a consequence, it was through the interpretation of sequential landscape patterns that the primary drivers of the riverine landscape dynamics have been inferred in different studies (Miller et al., 1995; Hohensinner et al., 2004; Geerling et al., 2006; Whited et al., 2007). A full range of phenomena, ranging from catastrophic events to predictable mean flow, generate the fluvial dynamics and fluctuating hydrological connectivity that characterizes intact river-floodplain systems (Jungwirth et al., 2002). Riparian succession tends to drive aquatic environments toward terrestrial landscapes, but erosion and deposition during low-frequency floods truncate those successional pathways. As a result, in a diverse landscape which contains landscape units at every stage of succession, irregular and anticipated, events drive hydrogeomorphological functions and, in general, allow the system to remain stable (Amoros and Wade, 1996).

Anthropogenic alterations of floodplains often disrupt the intensity, frequency and timing of the natural disturbance regime that is key to the ecological integrity of riverine environments (Ward and Stanford, 1995). The need and/or desire for new space to develop, occupy and/or farm has greatly disturbed floodplains of small and large rivers alike. As a consequence, floodplains are among the most threatened ecosystems in the world despite their biological importance (Tockner and Stanford, 2002). At the Ebro River, in northeast Spain, the promotion of dam construction for irrigation purposes during the last century (Pinilla, 2006), resulted in the accelerated occupation of river margins and massive construction of flood protection structures. In the middle stretch of the Ebro, only about 4% of the floodplain is covered by natural vegetation (Ollero, 1992). Regato (1988) reported that natural vegetation had been strongly modified within the Ebro River study reach by alteration of the fluvial dynamics; this was later confirmed by Castro et al. (2001). Floodplain habitats, therefore, must be a critical component of river management for the Water Framework Directive to be successfully applied on the Ebro River.

To achieve the restoration of threatened river systems, a complete understanding of geomorphological and ecological processes is required (Kondolf, 1998). Such an understanding will serve as a basis to predict the potential effects of performing site-specific restoration either alone or in combination with flow allocation on a basin-wide scale. In this paper, the landscape dynamics of one study reach in the Middle Ebro River are investigated, as well as changes in the natural flow regime and anthropic activities, in order to achieve the next tasks:

a) examine changes in hydrological and landscape patterns

b) identify the factors that best explain the natural ecotope succession and

c) propose a realistic restoration option with consideration of the landscape dynamics during the last century and the socio-economic context

2 Methods

2.1 Study area

The study reach was located in the Middle Ebro River, NE Spain (Fig. 1). This is the largest river in Spain (watershed area=85 362 km^2, river length=910 km, average annual discharge to the Mediterranean Sea=18 138 Hm^3) and is still geomorphologically active. The river meanders within this section (sinuosity=1.39, bank slope=0.050%), resulting in an average floodplain width of 5 km. Within the study reach, the mean discharge is 230 m^3/s and the elevation ranges between 175 m a.s.l. in the river channel to 185 m a.s.l. at the base of the scarp. The estimated area that would be inundated by the 10-y flood event (3000 m^3/s, 1927–2003) is 2230 ha, although only about 14% of that area would be inundated during a 1000 m^3/s flood event (0,37 y return period, 1927–2003), and only 4% would be flooded by a river discharge of 500 m^3/s. Upstream of the city of Zaragoza, the catchment area is 40 434 km^2 and the dam-equivalent capacity is 1637.19 Hm^3.

2.2 Hydrological analysis

Due to its main role in river-floodplain systems (Junk et al., 1989; Tockner et al., 2000), the pulsing of the river discharge, i.e. flood pulse, was used to characterize the hydrological patterns. It served as a basis to interpret landscape changes, although further analyses are required to interpret the direct effect of the components of the flow regime (magnitude, frequency, duration, timing, rate of change) over ecotope dynamics (see Poff et al., 1997). Daily average discharge, from 1927 to 2003 at Zaragoza, was provided by the Ebro River Basin Administration. This gauging station is located 12 km upstream of the study area and there are no major water diversions between the station and the study area; the discharge values, therefore, should be representative of conditions within the study area. A times series of flood events was generated from the original daily series. A flood event was defined as a series of one or more consecutive days with average daily discharge equal or higher than 600 m^3/s. For each flood event the duration, peak discharge and cumulative discharge were recorded. A magnitude-frequency analysis of flood events was conducted using the partial duration series approach, with the purpose of determining the recurrence time of characteristic flood events. The partial duration series approach was preferred over the annual maximum series, which is the most widespread technique, due its superior mathematical properties and robustness (Beguería, 2005). The series of flood events were fitted to a Generalised Pareto distribution, which is the limit distribution for a series of events over a fixed threshold (Cunnane, 1973). In order to interpret ecotope dynamics through the hydrological patterns, data were separated and analyzed for three different periods (1927–1957; 1957–1981; 1981–2003), which coincide with the time-spans between aerial pictures. Bankfull discharge, an important parameter controlling channel and floodplain morphology, was defined as the flood event with an estimated recurrence time of 1.58 y (see Dury, 1981). Similarly, recurrence times for other river discharge values were also estimated for further inter-period comparisons. Finally, the mean annual discharge at the Zaragoza gauging station was also calculated.

2.3 Landscape analysis

Ecotope maps (Fig. 1) were generated from a set of aerial photographs (1927, 1946, 1957, 1981, 1998 and 2003) to perform a landscape transition analysis using GIS techniques. The 1946, 1957 and 1981 photographs were black-and-white at different resolution scales (1:40 000, 1:33 000 and 1:18 000, respectively). They were rectified and georeferenced using LPS® 9.1 (ERDAS Imagine 9.1®). The 1927 images were supplied by the Ebro River Basin Administration as rectified aerial photographs (1:10 000) and georeferencing was performed with ArcGis 9.2®. Both maps and aerial pictures had been previously scanned at 600 dpi, yielding raster images with a pixel resolution from 1 to 2 m. Positional accuracy (n=20) in the studied floodplain averaged 5 m for all georeferenced images. Finally, 1998 and 2003 aerial pictures were supplied by the Aragon Regional Government as georeferenced images with a 1.0 and 0.5 m pixel resolution, respectively.

Three years of field campaigns served as a basis for the identification of ecotope types (Table 1). Landscape units were then delimited and classified following a simple interpretation-key, which was created using texture, colour, tree density, vertical structure, position in the landscape or previous channel migration dynamics. Landscape data were digitized using ArcGis 9.2® with a fixed scale of 1:3000. When possible, a stereoscope was used to exploit the original quality and vertical information of the aerial photos. All patches smaller than 64 m^2 were eliminated and vector maps were rasterised to a 10×10 m grid using ArcGis 9.2®.

To explore the relationship between landscape structure and human modification of river-floodplain interactions, ecotope maps were progressively truncated by increasing the distance to the main channel by 100 m, up to 1000 m, and every 500 m from 1000 to 2500 m. This final buffer distance included the entire 10 y floodplain, which has been considered the reference area for the landscape metrics. Delineation of this reference area was refined by the Ebro River Basin Administration using remote sensing data and ground-truthing during the February 2003 flood, which peaked at 2988 m^3/s at the Zaragoza gauging station (Losada et al., 2004). For all buffers considered in this study, Fragstats 3.3 (McGarigal and Marks, 1995) was used to calculate the area and percentage of land occupied by each ecotope category (CA and PLAND), as well as ecotope diversity using the Shannon Index (SHDI).

To examine ecotope change, transition matrices and maps were produced for each time span using IDRISI Kilimanjaro® (CrossTab). A general ecotope succession model (Fig. 2) was then created from the interpretation of transition matrices and previous research on vegetation dynamics (Braun Blanquet and de Bolós, 1987; Regato, 1988). Every ecotope transition was classified either as a Natural transition (succession (SUC), rejuvenation (REJ) or stability (STA) according to the succession model (Fig. 2)) or as human-affected transition (towards the “Anthropic” type). Using the cartographic ecotope data from the previous year, we determined how ecotope types developed from the initial patchwork. For this analysis, the importance (%) of SUC, REJ and STA during the analysed snap-shots was represented in triangular ternary plots discarding the human-affected transitions , as recently constructed by Geerling et al. (2006). Conversely, using the following year as the reference point we identified which fraction of the final patchwork belonged to each successional process.

3 Results

3.1 Hydrological analysis

Our analysis revealed a clear decrease in the mean annual discharge at the Zaragoza gauging station since 1981. Although discharge showed an apparent increase in the first two periods (1927–57 and 1957–1981), rising from 7930 to 8720 Hm^3/y, it fell to 5834 Hm^3/y during the last twenty years. The magnitude and frequency of floods in the Ebro River also decreased since 1981 (Fig. 3). Similar-magnitude discharges were estimated to occur with similar frequencies from 1927 to 1981, after which their periodicity declined. For example, a 3000 m^3/s event, which served to delimit the floodplain area, had a recurrence time of 8 y and 10 y in the periods 1927–1957 and 1957–1981, respectively. From 1981 and 2003, however, the frequency of an event of that magnitude decreased, with a recurrence time of 60 years. Similarly, the bankfull discharge dropped slightly from 1980 to 1917 m^3/s between the first and the second time periods, but diminished substantially to 1410 m^3/s in the 1981 to 2003 period. The number of flood events in which the peak exceeded the bankfull discharge has decreased in since 1981 (Table 2) although no real drop was visible in the per year occurrence. The magnitude and duration of these flood events were higher before 1981, although its relative proportion with respect to the total number of floods has increased over time. The number and frequency of floods that peaked below bankfull discharge have progressively dropped over the last 80 years, going from 206 sub-peak events in the 1927–1957 period (7.10 events per year), to only 90 such events in the 1981–2003 period (4.09 events per year) (Table 2). However, duration and magnitude of sub-peak events have oscillated, reaching a maximum (4.58 d per event) in the 1957–1981 period, and a minimum (3.37 d per event) in the most recent period, showing no clear trends.

3.2 Landscape analysis

Ecotope maps show how drastically the landscape structure has changed from 1927 to 2003 (Fig. 1). Ecotope diversity has decreased over that same period. The Shannon Diversity index (H) of the entire floodplain area, which corresponds to the 2500 m buffer, dropped from 1.78 in 1927 and 1946 to 1.08 in 1998 and 2003 (Fig. 4). In 1981, this index was slightly lower than in 1998. In addition, there has been a spatial change in ecotope diversity within the floodplain relative to proximity of the main river channel. Prior to 1981, ecotope diversity peaked at a distance of 300 m from the river bank and then decreased with increasing distance from the river; the 1946 spectra shows a secondary, though slight, peak at 900 m. However, the 1981, 1998 and 2003 data show maximum ecotope diversity at just 100 m from the main channel, followed by a rapid and steep drop.

Elongated meanders were present in the 1927 maps, but these oxbow channels were cut-off before 1946 (Fig. 1). Lateral accretion caused the main channel to migrate between 1946 and 1981, and established its current location. The area of the main channel decreased over the study period (8.24% in 1927 to 5.33% in 2003), whereas its relative importance within the natural ecotopes area increased (16.29% in 1927 to 20.16% in 2003) (Table 3). In contrast to the aerial decrease in most of the natural ecotopes, human-occupation of the river space has markedly increased in importance, especially between 1946 and 1981 (Table 4). This change appears true not only for the outer margins of the floodplain, where incremental impacts would be expected, but also the natural riparian corridor, adjacent to the main channel, which has narrowed considerably (Fig. 1).

The ecotope transitions were grouped into the three time periods in accordance with the hydrological analysis (Fig. 5):

a) 1927–1957, transitions 1 and 2,

b) 1957–1981, transition 3 and

c) 1981–2003, transitions 4 and 5.

Natural ecotopes at different successional stages (Table 1) evolved in a distinctive manner which influenced their area coverage in the final year of each transition (Table 3). During the first phase, channel avulsion after cut off of the meanders (Fig. 1, 1927–1946) increased the area of the ecotopes during the initial stages (Table 3). However, younger ecotopes decreased in importance between 1946 and 1957, when conversion of natural landscapes to agricultural fields (Table 4) resulted in marked changes in the "gravel" and "fines". Ecotope rejuvenation (REJ) and stability (STA), on one hand, were in balance with succession (SUC), which was even impeded for the "gravel" and "fines" patches in the 1927–1946 transition (Fig. 5). For the intermediate stages, distinct successional pathways (Fig. 2) resulted in a different dynamics. "Intermediate" and “buried trees”, normally located adjacent to the main channel, showed high REJ percentages while their areal coverage decreased between 1927 and 1946. This trend prevailed until 1956, although their areas remained stable despite anthropic pressure (Table 4). However, succession was balanced with stability during this same period, as evidenced by an approximate two-fold decrease in “macrophytes” area. The remaining patches were highly affected by conversion to agricultural fields along during 1946–1957, mainly due to loss in the outer floodplain (Table 4, Fig. 1). The area occupied by emergent vegetation remained stable between 1946 and 1957 . For “herbaceous” and “intermediate island”, no clear trends were detected. Finally, even though patches of the various mature stages were renewed progressively between 1927 and 1957, their areal coverage did not decrease proportionally (e.g., “mature”), and, in some cases, even increased (e.g., “scattered trees”).

From 1957 to 1981, trends were similar to those in the first time period for “open water” and “gravel”, but SUC became dominant for “fines” and “young island”. During this period, only the “gravel” area diminished (Table 4). For intermediate stages, SUC also emerged as the dominant process, although REJ was also important. Their areas decreased due to the high rates of conversion to “anthropic” and the low stability (Fig. 5). Referring to mature ecotopes, rejuvenation and anthropization restricted the establishment of “scattered trees” and “mature”. However, those ecotopes became dominant, with the latter (“mature”) even increasing its importance. During the last period (1981–2003), the areas containing ecotopes at initial and intermediate stages decreased, with the exception of macrophytes. In contrast, “mature” and “scattered trees” accounted for about 50% of the floodplain (Table 3). Young islands existing in 1981 were destroyed and re-established in another location along the main channel (Fig. 1), while “mature islands” first appeared in 1998. All ecotope types showed a slight trend towards STA between 1981 and 1998, with the exception of “island” ecotopes. During that transition, REJ became nearly nonexistent (Fig. 5). Finally, all ecotopes showed increasing signs of stability after 1998, despite the potential erosive effect of a 60 y flood (1981–2003) in February 2003.

In Sect. 1, the discovery of America was described. Here we will outline the subsequent history until the present. This is best summarized in Table 1.

As can be seen from Table 1, there is almost no mention of geomagnetism or the magnetosphere at all. This sorry situation is discussed further and explained away in Sect. 4.

4 Discussion

4.1 Changes in hydrological and landscape patterns

Over the last century, the natural flow regime in the Middle Ebro River has been modified by progressive river flow regulation and anthropization of the catchment area. However, it has been since 1981 that discharge magnitude and variability have markedly decreased (Fig. 3, Table 2). The mean annual discharge within the study reach has declined approximately 30% since 1981, coinciding with the decrease of bankfull discharge. Various researchers have suggested that this phenomenon has been caused by the progressive increase of evapotranspiration due to higher temperatures, reforestation of abandoned agricultural fields in mountainous areas, increase in reservoir water storage (volume and surface area) and the expansion of irrigated farmlands (Ibanez et al., 1996; Ollero, 2007). In basin areas upstream of the study reach, a sharp increase in the total equivalent capacity of reservoirs occurred between 1950 and 1980, in parallel with the expansion of irrigated land. However, the emphasis on agricultural production since the 1980s was driven to a large degree by the cultivation of water-hungry crops such as rice, fruits or vegetables (Frutos et al., 2004). In addition to this increased demand, precipitation peaked during the 70s in nearly all of the Ebro Basin (Abaurrea et al., 2002), which may have helped to dampen the effect of human impacts on the system. Flood events, flow and flood pulses (see Tockner et al., 2000) have shown distinct patterns of change in their frequency, magnitude and duration (Table 2). Since 1981, events above the bankfull discharge decreased in magnitude and duration while those below bankfull discharge decreased only in number. The management of the largest reservoirs for irrigation purposes might explain those trends. In winter, the number and magnitude of floods is dampened using the existing flood control infrastructure in order to store water for summer, when irrigation demand is high. Given the winter storage goals, the capacity of flood-control systems to mitigate large floods in early spring, when the snowmelt occurs, is minimal. This has been previously described for dams located in the Pyrenees, which are often at or near capacity at the onset of spring floods (Lopez Moreno et al., 2002).

Landscape structure seemed to adapt to changes in the flow regime, although such adjustment was altered by human disruptions of river-floodplain interactions. Both human occupation of the river space and dyke construction have accelerated the evolution towards a less diverse landscape, and modified the spatial patterns of landscape diversity (Fig. 4). The highest ecotope diversity (ED) was observed prior to the 1960s because it was during that time that construction of major flow regulation infrastructure began that would truncate the successional pathways. Moreover, flood events maintained a diverse array of landforms in areas adjacent to the main channel, what is not reflected in the spectra after 1957 might due to the effect of dykes. Diversity peaked at 300 m from the river channel (Fig. 4), where the progressive dominance of "anthropic", intermediate and mature ecotopes (Fig. 2) forced a decline in diversity. Prior to 1957, large natural patches in the outer floodplain (Fig. 1) caused diversity to be similar in 1927 and, 20 years later, in 1946. However, agricultural expansion in the floodplain substantially lowered diversity only 10 years later in 1956. Conversion from natural to anthropic ecotopes proceed almost entirely from 1946 to 1981 (Table 4), resulting in a two fold increase of the area covered by human-managed ecotopes (Table 3). After abandonment, some of those human-manages patches have been covered by natural vegetation, what explains the slight increase of ecotope diversity since 1981 (Fig. 4).

The drop in ecotope diversity after the 1960s might be explained, in part, by changes in hydrology, which promoted the decrease of ecotopes at the initial successional stages (Table 3). However, the magnitude of river flow and fluctuations in river discharge between 1957 and 1981 did not greatly differ from the previous period of 1927 to 1957 (Fig. 3). Therefore, it was the extensive implementation of flood protection structures along the river banks that was the most likely factor disrupting river-floodplain interactions. Although defences have been constructed along the Ebro River for centuries (Ollero, 2007), within the study reach almost all modern and effective flood protection structures were built between 1960 and 1980 (Ollero, 1992), and they are reinforced after every large flood. Thus, the strong dominance of mature ecotopes since the 1990s has been in response to the synergic effect of flow regulation and flood protection which has severely reduced natural changes within the floodplain. In addition, riverbed incision from dam construction probably counteracts the interaction between the main channel and its adjacent ecotopes during floods. Vericat and Batalla (2006) reported a river bed incision of 3 cm per year for the lower Ebro.

4.2 Natural ecotope succession

Human alteration of river-floodplain interactions, which occurred sequentially, prevailed over the natural drivers of floodplain dynamics since 1957. This promoted a different ecotope dynamics, as well as distinct initial conditions, for each time period considered in this study:

a) Channel Migration (1927–1957): unmodified flow regime and absence of flood protection, high conversion to anthropic landcovers took place at least since 1946,

b) Vertical Accretion (1957–1981): unmodified flow regime but establishment of flood protection (Ollero, 1992), high rates of conversion to anthropic landcovers and

c) Homogenization (1981–2003): modified flood regime and dyke construction, conversion to anthropic ecotopes with a great reduction in natural ecotopes.

During the first phase (1927–1957), the river-floodplain interactions during flow pulses not only stabilized part of the area occupied by initial and intermediate ecotopes, but also compromised the ongoing succession through main channel migration. Flood scouring forced larger patches of mature ecotopes to be located at the outer floodplain (Fig. 1), whereas flood events were sufficiently robust to rejuvenate mature patches located adjacent to the main channel (Fig. 5). Between 1946 and 1957, the elevated river-floodplain connectivity allowed for rapid readjustments to disturbances within the watershed, which explains the differences between initial and intermediate ecotope areas between 1946 and 1957 (Table 3) and the percentage belonging to earlier stages (Table 5).

During the second phase (1957–1981), river-floodplain interactions were strong enough to allow channel migration before the main channel adjusted to its "straitjacket" (sensu Lamers et al., 2006), and therefore, rejuvenation occurred at every successional stage (Fig. 5). The intense conversion to human-managed ecotopes restricted natural patches to the river corridor (Fig. 1), while lateral accretion was progressively constrained by dyke construction. As a consequence, succession was probably accelerated by higher vertical accretion rates. Steiger et al. (2001) described this trend for a riparian area over a 30-y period in the Garonne river.

During the last period (1981–2003), the synergic effect of a modified flow regime and flood protection impeded ecotope rejuvenation, with the exception of in-channel ecotopes (Fig. 5). Between 1981 and 1998, the effect of non-erosive floods caused succession to proceed for the initial and intermediate ecotopes, increasing the importance of mature ecotopes at the end of the period (Table 3). The last examined transition period (1998–2003) revealed strong system stability (Fig. 5), despite the potential effects of a 3000 m^3/s (60 y; 1981–2003) in February 2003. According to Amoros and Wade (1996), tremendous quantities of external energy are required to revert succession because in mature ecotopes, which accounted for 50% of the natural ecotopes in 1998 (Table 3), succession is driven by autogenic processes. Indeed, only bank erosion at localized points was detected between 1998 and 2003.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

4.3 Restoration options for the Middle Ebro floodplains

As described by Stanford et al. (2005), floodplain elements tend to persist in natural river systems, although their spatial distribution shifts over time due to flow-related changes. At the study reach this was observed until 1957, as shown by the proportion of ecotopes at different successional stages (Table 3, right). Under such natural conditions, erosion during low-frequency floods truncate successional pathways (Amoros and Wade, 1996). Peaks at the diversity spectra (Fig. 4) indicate that it occurred at areas closed to the main channel until 1957, before dykes started to be set. It seems, therefore, that hydrological and landscape patterns prior to 1957 allowed natural ecotope dynamics. Since 1957, those patterns have been markedly modified, and so river-floodplain interactions responsible to maintain natural ecotope dynamics. Consequently, the ecotope diversity and dynamics observed between 1927 and 1957 is considered by the authors as a valid reference situation if a more natural functioning of the river-floodplain system wants to be achieved through ecological restoration.

To plan and accomplish this, landscape and hydrological constraints must be considered. Existing landscape disturbances (dykes, vegetation encroachment, and raised surfaces) will limit the restoration success if the natural flow regime is recovered to a more historical condition. Although surface and groundwater connectivity would be enhanced, the erosive effect of floods would be strongly counteracted by artificial dykes constructed at convex banks and vegetation encroachment at concave banks. Also, accretion would be accelerated in the outer floodplain, as it has been observed during the period 1957–1981. Ecotope dynamics could increase in the main channel and adjacent areas. Given these likely conditions, the overall ecotope diversity would not substantially change, although it could increase along the riverbanks. Similarly, hydrological patterns will limit the restoration success if floodplain topography is modified to enhance connectivity. A dynamic corridor could be created if dykes are removed or re-located and floodplain height is lowered, but the current flow regime is not adequate to ensure self-sustained processes over the entire floodplain area. Moreover, the main channel will probably adjust to new conditions after a certain period of time, as it was observed during 1946–1957.

To deal with such landscape and hydrologic constraints, we strongly recommend that river management decisions and scientific knowledge should be integrated across scales, as pointed out by Hughes et al. (2001). At basin scale, alternative strategies would need a more integrated use of natural resources, consisting primarily of soil and water (Comin, 1999). Beyond that, however, the current land uses within the Ebro Basin territory must also be integrated into a management plan, as performed for other threatened floodplains (Rhode et al., 2006; Hale and Adams, 2007). At present, 80% of the Ebro water demand is diverted for agriculture and farming (Frutos, 2004), accounting for about 40% of the mean annual discharge. This trend is not likely to be changed because of further irrigation development is planned (www.chebro.es). At reach scale, public reclamation of agricultural lands for restoration purposes seems possible due to the current socio-economic context. The average age of landholders has increased through time, and a high percentage of the crops are only profitable due to agricultural subsidies. With regards to flood protection structures, decisions concerning on dyke reallocation rely entirely on the Ebro Basin administration.

Under this scenario, the more realistic option is to create a dynamic river corridor where the river is the engine behind system maintenance. Within this corridor, landscape patterns should mimic those observed in 1927 and 1957 if restoration succeeds. With regard to flow regime, it would be unrealistic to attempt to restore the magnitude of river discharge, also because the forecast of climate and global changes establishes a potential reduction of the river discharge in the Ebro basin (Lopez-Moreno et al., 2008). Instead, efforts should focus on mimicking the other components of the flow regime (frequency, duration, timing, rate of change) since that will more likely contribute to sustain the riparian dynamics (Poff et al., 1997; Bendix and Hupp, 2000; Hughes and Rood, 2003; Stromberg et al., 2007). To reach the desirable self-sustainable ecotope dynamism, the extent of the river corridor should adapt to the restored flow regime. As exemplified by Greco et al. (2007), geomorphological dynamics are necessary to maintain such dynamics. The current landscape constraints (dykes, raised surfaces) have to be eliminated within the dynamic river corridor. It should be achieved by an initial economic investment, which will be required to be periodic if the self-sustained dynamism is not reached. This strategy has been proposed as a valid compromise between the need for flood protection and the growing demand for ecosystem rehabilitation in highly regulated rivers (Baptist et al., 2004). Additional monitoring, on a decadal–scale, will be required to evaluate the success of previously defined restoration plans, redefining them if key parameters change (Hughes et al., 2005).

5 Conclusions

Flow regulation, human occupation and construction of flood protection structures have modified landscape structure and dynamics in the middle Ebro River. At present, the fluvial landscape is less diverse and dominated by mature stages and anthopic ecotopes, river-floodplain interactions are counteracted by dykes, and hydrological patterns are different, in terms of pulses of the river discharge, to those observed prior to river regulation (1957–1957). It seems, therefore, that a more natural functioning of the river-floodplain system should be achieved through ecological restoration. To accomplish this goal, ecotope diversity and dynamics observed between 1927 and 1957 is a valid reference situation. When implementing restoration, managers should consider the current hydrological and landscape constraints (dykes, vegetation encroachment, and raised surfaces) and the socio-economic context at basin and reach scale. The more realistic option is creating a dynamic river corridor whose extent should adapt to the restored flow regime. An initial economic inversion is necessary to reallocate dykes and lowering floodplain height; however, it might be required periodically if self-sustained restoration is not achieved within this dynamic river corridor.

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Table 1. Ecotope types used to define landscape units.

Ecotope	Successional Stage	Description
Main Channel	–	Area occupied by main channel
Gravel	Initial	Covered by gravel, adjacent to the main channel
Fines	Initial	Covered by fine substrate, adjacent to the main channel
Open water	Initial	Flooded areas with no emergent vegetation
Young Island	Initial	Located in-shore, covered by gravels
Intermediate	Intermediate	Closed canopy (>75%), young individuals
Buried trees	Intermediate	Coarse substrate, clustered young trees
Macrophytes	Intermediate	Covered by emergent vegetation
Herbaceous	Intermediate	Absence of trees, not adjacent to the main channel
Inter. Island	Intermediate	Located in shore, not covered by gravels or mature trees
Scattered Trees	Mature	Fine substrate, clustered mature trees.
Mature	Mature	Closed tree canopy (>75%), mature individuals
Mature Island	Mature	Located in shore, covered by mature trees
Anthropic	–	Agricultural fields or poplar groves

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀▌ | ▶▌
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 2. Number, duration and accumulated mean discharge of flood events at the Zaragoza gauging station. Data were analyzed separately for the three temporal periods. Flood events were categorized according to the estimated bankfull discharge.

Period	Peak Discharge (m^3/s)	Events		Duration (d)		Cumulative Discharge (m^3/s)	
		total	per year	total	per event	total	per event
1927–1957	600<x>1980	206	7.10	811	3.94	738098.95	3583.00
	x>1980	21	0.72	335	15.95	437880.21	20851.44
	TOTAL	227	7.82	1146		1175979.16	
1957–1981	600<x>1957	146	5.84	669	4.58	593994.61	4068.46
	x>1957	20	0.80	310	15.50	406952.18	20347.61
	TOTAL	166	6.64	979		1000946.79	
1981–2003	600<x>1410	90	4.09	303	3.37	246465.12	2738.50
	x>1410	16	0.73	161	10.06	180496.64	11281.04
	TOTAL	106	4.82	464		426961.76	

Table 3. Area (%) covered by each ecotope in each year. Percentages are calculated for the total floodplain area (2230 Ha) and for the area occupied by natural ecotopes. Sub-totals by succesional stage (see Table 1) are also displayed.

ECOTOPE	AREA (%)											
	Floodplain Area						Area occupied by Natural Ecotopes					
	1927	1946	1957	1981	1998	2003	1927	1946	1957	1981	1998	2003
Main Channel	8.24	9.08	6.83	6.63	5.25	5.33	16.29	17.36	19.93	27.98	19.84	20.16
Gravel	7.96	10.05	6.84	2.60	1.30	1.18	16.08	19.19	19.97	10.97	4.90	4.45
Fines	2.63	3.13	0.40	0.38	0.60	0.60	5.31	5.98	1.15	1.59	2.26	2.26
Open Water	0.48	1.62	0.81	1.03	0.69	0.73	0.98	3.09	2.35	4.33	2.64	2.75
Young Island	0.64	1.66	0.16	0.46	0.17	0.17	1.65	3.17	0.47	1.93	0.66	0.66
INITIAL	19.95	25.54	15.04	11.1	8.01	8.01	40.31	48.79	43.87	46.8	30.3	30.28
Intermediate	5.41	5.07	4.59	2.43	1.22	1.28	10.95	9.68	13.42	10.23	4.62	4.84
Buried Trees	6.18	3.02	2.68	1.22	0.30	0.35	12.50	5.78	7.79	5.13	1.14	1.32
Macrophytes0	7.01	4.13	4.58	1.82	2.24	2.25	14.17	7.87	13.36	7.69	8.46	8.50
Herbaceous	0.08	0.08	0.73	0.19	0.52	0.51	0.14	0.16	2.14	0.79	1.97	1.93
Inter. Island	0.38	0.00	0.01	0.05	0.03	0.03	0.77	0.00	0.03	0.21	0.11	0.11
INTERMEDIATE	19.06	12.3	12.59	5.71	4.31	4.42	38.53	23.49	36.74	24.05	16.3	16.7
Scattered Trees	4.38	10.79	4.30	2.90	7.91	7.89	8.83	20.62	12.53	12.24	29.91	29.81
Mature	6.09	3.71	2.35	3.95	6.02	5.94	12.32	7.09	6.86	16.65	22.80	22.51
Mature Island	0.00	0.00	0.00	0.06	0.18	0.18	0.00	0.00	0.00	0.24	0.69	0.69
MATURE	10.47	14.5	6.65	6.91	14.11	14.01	21.15	27.71	19.39	29.13	53.4	53.01
Anthropic	50.53	47.66	65.73	76.29	73.56	73.56						
TOTAL	100	100	100	100	100	100	100	100	100	100	100	100

Table 4. Percentage of each natural ecotope category converted to "Anthropic" in each transition category. Also the entire area of natural ecotopes converted to "Anthropic" in each transition is shown.

Ecotope	1927–1946	1946–1957	1957–1981	1981–1998	1998–2003
Main Channel	0.67	1.22	1.89	0.62	0.00
Gravel	0.13	27.56	19.97	4.37	0.00
Fines	0.18	70.05	51.18	2.60	0.00
Open Water	0.31	5.98	6.71	1.88	0.00
Young Island	0.00	1.99	0.00	0.00	0.00
Intermediate	3.86	38.15	52.97	4.71	0.00
Buried Trees	14.65	52.03	35.33	2.97	0.00
Macrophytes	8.98	69.16	69.38	1.96	0.00
Herbaceous	0.00	60.98	82.41	0.24	0.00
Inter. Island	0.00	–	0.00	0.00	0.00
Scattered Trees	16.64	64.39	88.13	4.08	0.00
Mature	17.15	43.37	81.76	7.62	0.00
Mature Island	–	–	–	0.00	0.00
TOTAL (Ha)	73.06	449.80	326.07	17.619	0

Table 5. Percentage of each ecotope remaining from an earlier natural ecotope at the end of each transition.

Ecotope	1927–1946	1946–1957	1957–1981	1981–1998	1998–2003
Main Channel	0.00	0.00	0.00	0.00	0.00
Gravel	31.54	41.05	45.66	36.64	0.00
Fines	5.23	49.94	44.21	35.54	0.00
Open Water	29.31	47.52	41.93	13.20	0.00
Young Island	18.35	39.93	29.77	85.03	0.00
Intermediate	42.73	68.53	64.87	59.08	5.42
Buried Trees	45.88	87.21	87.20	37.68	13.32
Macrophytes	0.66	34.24	16.83	14.92	0.00
Herbaceous	2.65	79.25	90.13	71.51	0.00
Inter. Island		100.00	18.89	82.10	0.00
Scattered trees	38.74	28.07	77.87	31.96	0.00
Mature	49.77	49.62	85.73	38.65	0.00
Mature Island	–	–	100.00	100.00	0.00

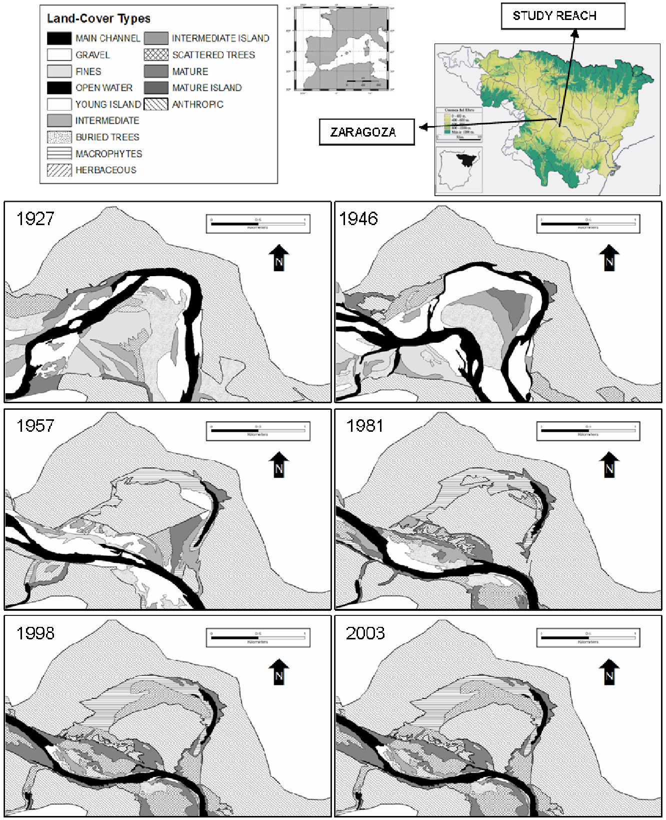

Fig. 1. Ecotope maps for a representative part of the study reach, including each of the six years considered in the study. River flow is from the upper left to lower right. There has been essentially no main channel migration between 1981 and 2003. No significant changes were detected between 1998 and 2003.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀◀
▶▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

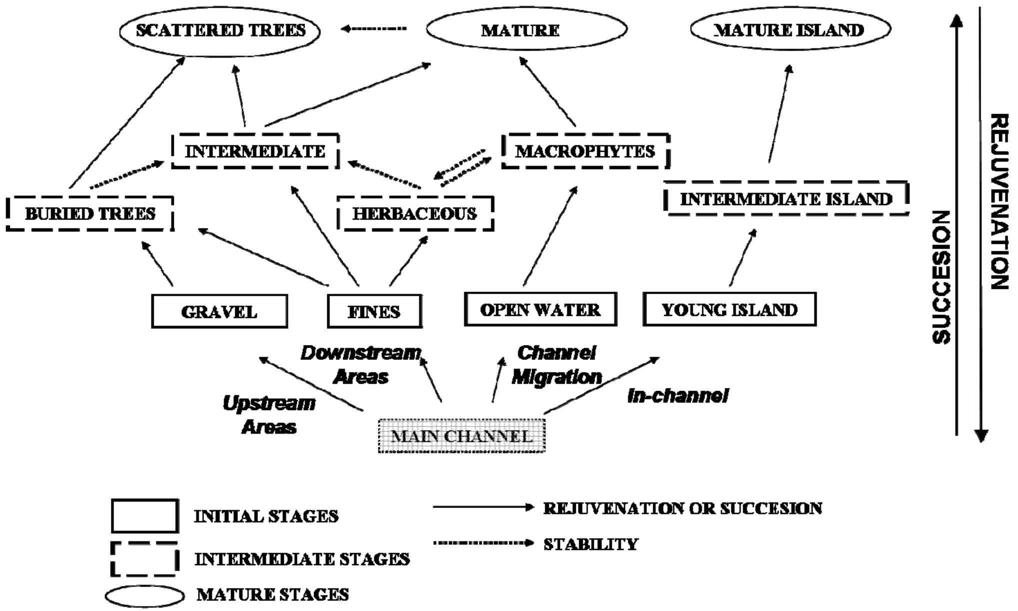

Fig. 2. Ecotope succession scheme.

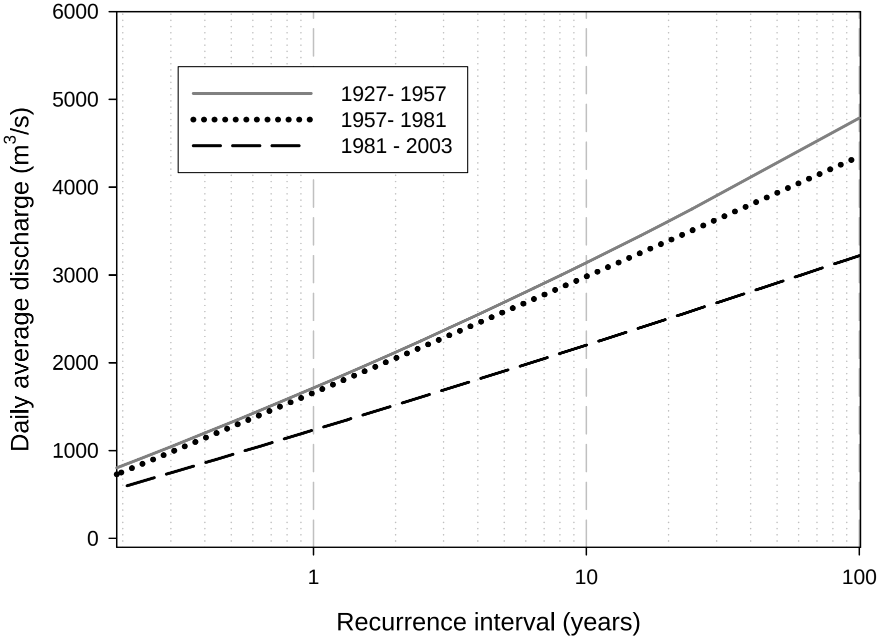

Fig. 3. Magnitude-frequency plots illustrating reduced frequency of high-discharge events in more recent years.

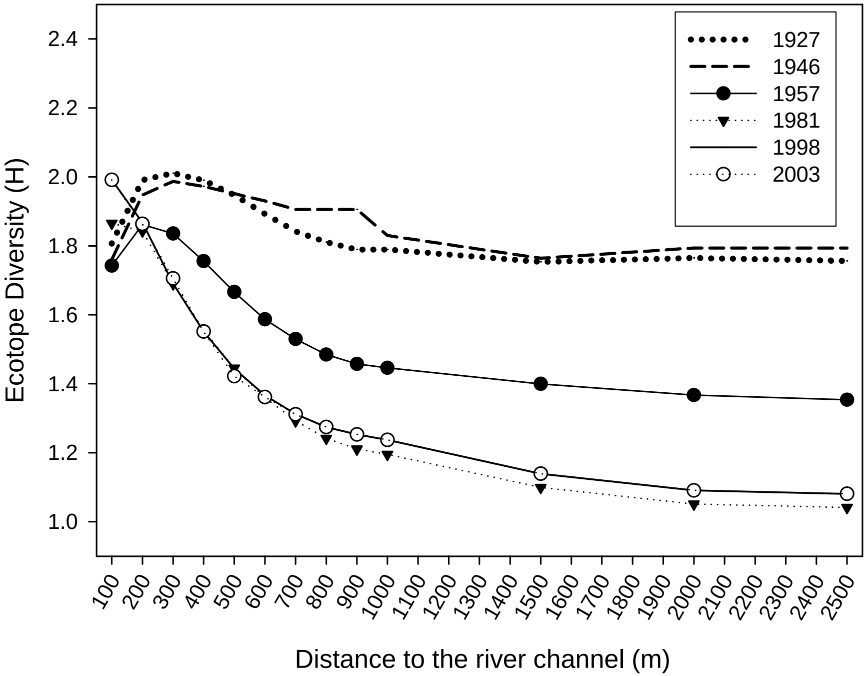

Fig. 4. Ecotope diversity as a function of distance to the river channel. Note that 1998 and 2003 plots are superimposed.

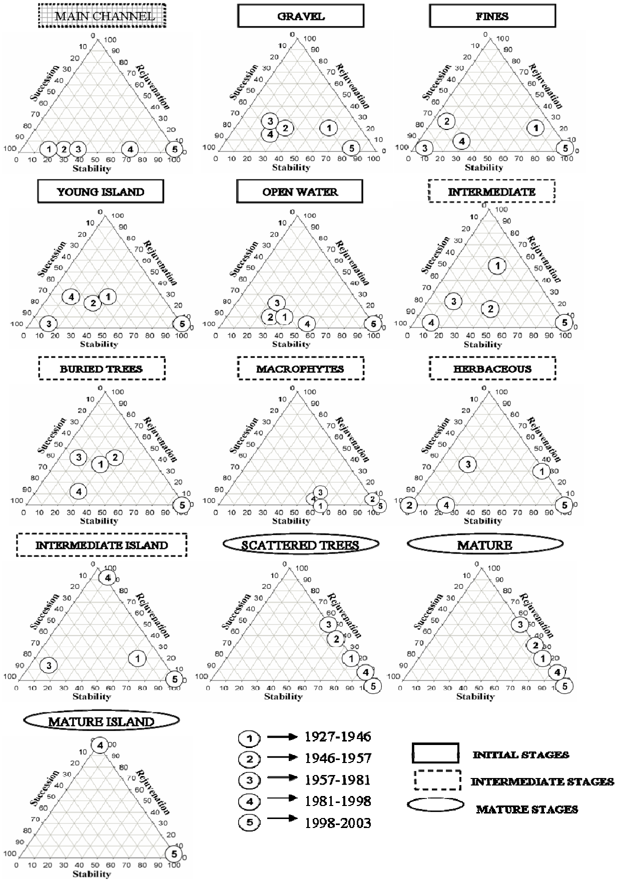

Fig. 5. Ternary plots for ecotope succession, rejuvenation or stability, considering the fraction of the ecotope not converted to "Anthropic". "Intermediate Island" did not exist in 1957 while "Mature Island" appeared in 1981.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀▮ | ▶▮
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion