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Long-term human-generated alterations of Tagus River: Effects of hydrological regulation and land-use changes in distinct river zones

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ABSTRACT

Large rivers on the Iberian Peninsula reflect a long-history of human interventions and natural disturbances in the fluvial corridors and on the surrounding valleys. In this study we aim to characterize the river morphology in pre-regulation times and understand the morphological changes of the large river Tagus (Central Portugal), across space and time. For this, we used comparable military thematic maps from three dates (1855, 1940 and 2000) and evaluated the river landforms, including sinuosity, aquatic, geomorphic and riparian aspects, in three geomorphological zones (Upland, Middle, and Lowland) using a Geographic Information System (GIS). We related the landform variations to the hydrological alterations and to Land-use Land-Cover (hereinafter LULC) changes at valley level. Hydrological data were achieved by simulating river flow regime using the Soil and Water Assessment Tool (SWAT) model. LULC data was obtained by on-screen digitizing of the military thematic maps complemented with ancillary bibliographic information. Metrics for channel form, aquatic and riparian features were quantified in 51 sampling units of 2500 m-long river sections for each period to describe the river morphology. Shannon-Wiener Index (H') was applied as a descriptor of the morphological diversity.

Data analysis revealed a narrowing of the main channel, an overall reduction of the sinuosity, a smaller number of instream geomorphic units and abandoned lateral channels on the most recent period. Morphological alterations were driven primarily by the reduction of floods and sediment inputs, caused by streamflow regulation, while the agricultural intensification, the augment of forest plantations and the reduction of the Mediterranean scrublands induced changes in sediment dynamics and altered the riparian connectivity. The Upland zone showed the highest morphological alterations switching from a historical high-energy section to a low-dynamic zone. We also observed a high morphological variability in the Middle course exhibiting multi-faceted gradients of change, while the Lowland zone reflected continuous but less pronounced modifications. River management planning should express the insights of how past and present human alterations affect morphological processes in river-floodplain systems, particularly taking into account river zones' specificities and how they may react or constrain potential restoration processes.

1. Introduction

Large rivers are central components of landscapes that connect lands, biota and human societies and provide fundamental resources, and services – water, food, materials, energy, irrigation, transportation, and recreation. However, the quest for human security, and the demand for goods and services from rivers and their floodplains frequently disregarded the hydrodynamic features of rivers, their channel landforms and the health of aquatic and river ecosystems (Burge, 2007). Therefore, large rivers reflect the imprint of a long history of human interventions to control the spatial and temporal dynamics of water availability and natural hazards such as floods and droughts and to take the best profit of water resources. For instance, Nilsson et al. (2005) reported that the economic activity per unit of water was 25 times higher in large dammed rivers than on unaffected catchments, and the Gregorys' (2006) revision, based on more than 200 studies, referred tenfold differences in size, shape, and composition of cross-section of impaired river channels as opposed to natural channels. Deforestation, reforestation, fire, mining, agriculture, urbanization, and streamflow regulation for power, irrigation and flood protection are pointed as

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major stressors of the river systems worldwide (Tockner and Stanford, 2002). The consequences of these non-natural sources of change are a generalized degradation of the river morphology and the geochemical and ecological processes, both at reach and catchment-scales. Man-induced changes alter erosion, transportation and sediment dynamics which frequently increase bank erodibility, cause avulsions, incision of river beds, development of single-thread channels and the simplification of channel profiles and narrowing river corridors (Gurnell and Petts, 2002; Mendoza et al., 2019). Besides the alterations on channel dimensions, forms and features – channel morphology-, degradation of river morphology also reflects an ecological functioning perspective and the interplay with streamflow alterations and Land-use Land-Cover (LULC) dynamics (Newson and Large, 2006). In the last four decades, we perceived an increasing awareness of the detrimental effects of the reckless overuse of water resources and river environment, brought by hydroecologists, river managers, researchers, and stakeholders. The rise of environmental and socio-economic concerns pressured the development of environmental regulations and environmental rewards, which calls for a better understanding of ecological and geomorphological processes of rivers and their trajectories of change (Grabowski et al., 2014; Gonzáléz del Tanago et al., 2016).

While tracking large-scale geomorphic river changes in the last decades can be done using aerial photographs, orthophotomaps, satellite imagery and emerging techniques as LiDAR (e.g. Rinaldi, 2003; Dufour et al., 2015; Aguiar et al., 2016, Lallias-Tacon et al., 2017), finding sources of information that date back one or more centuries is challenging (Hooke and Redmond, 1989; Magliulo et al., 2016). Geohistorical approaches using old maps are becoming increasingly recognized as resources for understanding changing landforms and the historical stability of rivers (e.g., Taillefumier & Piégay, 2003; Forget, 2013; Uribelarrea et al., 2003; Zlinszky and Timár, 2013; Ziliani and Surian, 2016). Nevertheless, there are still few diachronic studies using old cartography, and especially in large rivers (Forget, 2013).

In the present study, we used military thematic maps from the19th, 20th and 21st centuries Tagus River, depicting a period of 145 years for more than 120 km in Portuguese territory, representing three distinct geomorphological zones. Using a GIS-aided analysis and data from historical literature and reviews (e.g. Guerra, 1861), we aspired to reconstruct the trajectory of past change in pre-regulation times of Tagus River landforms, including sinuosity, aquatic, geomorphic and riparian aspects, hereafter named as 'river morphology'. We used Shannon-Wiener Index (H') as a descriptor of the morphological diversity across space and time. Moreover, we aim to determine the human perturbations on the river itself (mainly by hydrological regulation) and on the valleys and floodplain (mainly by LULC) that contributed to these changes.

The studies of Azevêdo et al. (2004, 2009) on the Portuguese part of Tagus describe numerous historical interventions on the channel of Tagus since the 16th century, aiming to protect from floods, enlarge agricultural lands and allowing navigation. Impressive alterations were made in the 16th century, for example the displacement of a 10 km long channel of Tagus by 1 km northwards to avoid siltation by sterile sands (crevasse splay deposits) in the agricultural soils of the Crown, as well as the blasting of bedrock to make the river navigable from Portugal to Spain. Despite these interventions, the 18th century Tagus still had a dynamic character, which was progressively lost with the regulation works that started on the second half of the 19th century (Guerra, 1861), and culminated with a boom of dam construction for hydropower and irrigation by the middle of 20th century. At the same time, irrigated lands increased around 25 times since 1940 (Azevêdo et al., 2004). Nowadays, Tagus streamflow is strongly regulated by more than 70 large dams, and hundreds of small hydropower plants, and weirs.

In the present study we hypothesized that:

Hypothesis H1 (*Morphological zone divergence*): River morphology will show distinct magnitudes and trajectories of change in distinct river zones and

Hypothesis H2 (*Human-induced explanation)*: Hydrological alterations and LULC change both contribute to the differences in the river morphology of Tagus River.

For this, we have used modelled hydrology and recorded LULC at valley level, using ancillary bibliographic information and military thematic maps from 1855 (pre-regulation), 1940 (low-regulation) and 2000 (high-regulation).

With the proposed approach, we intended to understand the Tagus River morphological changes, regarding sinuosity, aquatic, geomorphic and riparian aspects, and asses how hydromorphological processes have been triggered by human interventions, in distinct river zones. There are several Iberian research studies focused on specific physical morphological aspects, such as channel width, meanders width and length, bar migration, or developed in particular river segments (Azevêdo et al., 2004, 2009; Uribelarrea et al., 2003). However, fewer studies were devoted to a comprehensive understanding of the historical morphological changes of rivers and riparian vegetation on a regional scale level (e.g. Hohensinner et al., 2004). The results of this study enlarge our understanding on the characterization of the dynamics of large rivers under human influence and offer insights for the restoration of degraded sections of rivers.

2. Materials and methods

2.1. Study area and river zones

Tagus River is the largest Iberian river draining a catchment of approximately 80,500 km^2, of which 24,800 km^2 are in Portugal. The study was conducted in the Portuguese part of Tagus, a typical Mediterranean climatic zone (Rivas-Martínez et al., 2017). The climate in the north eastern part of the study area is characterized by an average monthly temperature range between 6 and 22 °C and an average annual precipitation of 750 mm yr^{-1}, while in the South Western part of the study area the average monthly temperature ranges between 13 and 27 °C and the average annual precipitation is 550 mm yr^{-1} (APA, 2000). The hydrological regime has a strong seasonal and interannual variability, with high flows usually occurring in the winter, especially from November to February (495–650 m^3 s^{-1}) and low flows between June to September (140–187 m^3 s^{-1}) (Ómnias hydrometric station, monthly average; data series 1990–2016; available at https://snirh.apambiente.pt, consulted on May 2018).

The Tagus River cuts on rocks with ages that range from Pre-Cambrian to Quaternary. From the Portuguese–Spanish border to the village of Tancos (central Portugal) the Tagus run on old igneous and metamorphic rocks, whereas on the middle zone between Tancos and Vila Franca de Xira, incises the sediments of its Tertiary Basin, composing a wide alluvial plain of Pleistocene terrace sediments (Azevêdo et al., 2009). We thus considered three distinct zones: the 'Upland zone', characterized by steep slopes and geomorphologically constrained channels, the 'Middle zone', a low-medium energy river section, geomorphologically complex and the 'Lowland zone' in the lower Tagus draining over a thick alluvial bed within an agricultural irrigated land matrix (Fig. 1, Table 1). All zones were subjected to long-standing LULC change and hydrological alterations.

2.2. Sampling design and data collection

The river morphological evolution was assessed by means of a planform change analysis, supported by a Geographic Information System (GIS), using military thematic maps, with analogous legend and similar scale. Three dates were considered in the analysis in order to represent a gradient of increasing hydrological disturbance in the context of LULC changes: the historical date 1855 (pre-regulation); low-regulation-1940, and actual −2000 (high-regulation). We termed the historical data from 1855 as "Old", data from 1940 as "Int" (Intermediate) and data from 2000 as "New". The 19th century was

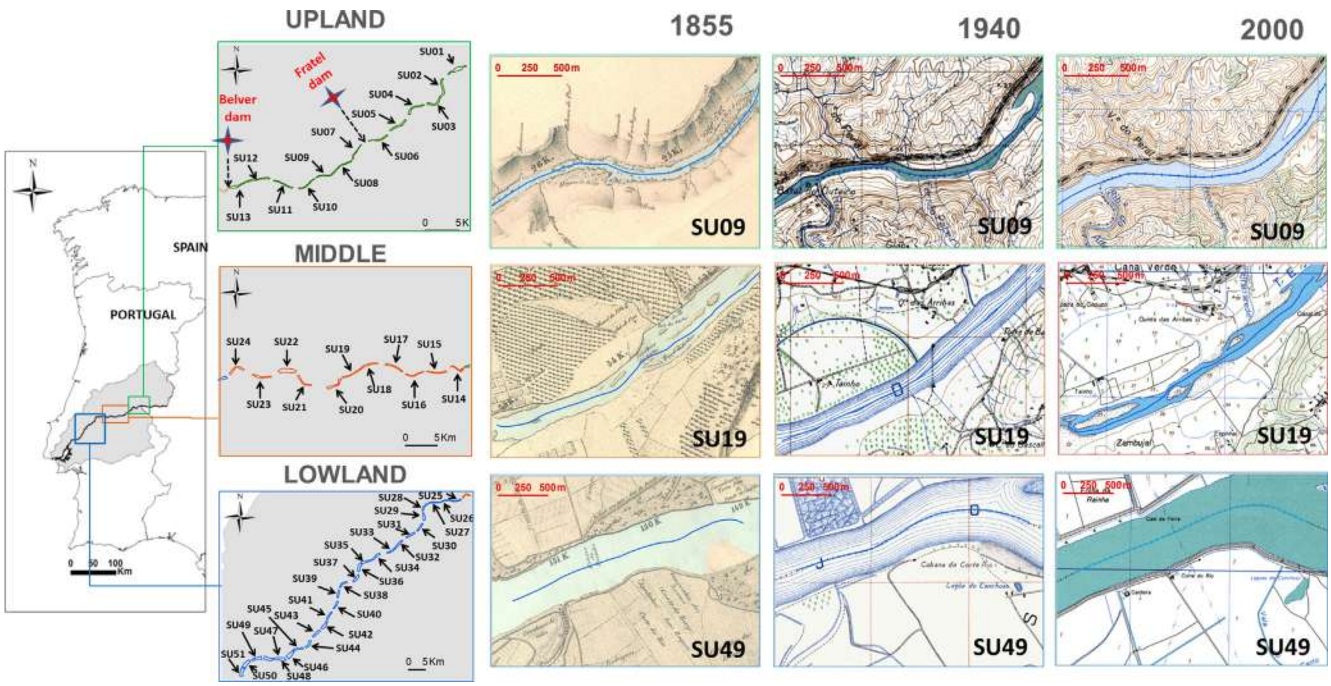

Fig. 1. Location map for Western Europe showing the Portuguese part of the Tagus River basin (grey area), the current location of Fratel and Belver dams and the Sampling Units (SU) location in the three studied river zones: Upland zone (green square), Middle zone (orange square) and Lowland zone (blue square). Vertical composite panels illustrate a Sampling Unit, in each river zone, for the three dates using military maps from 1855, 1940 and 2000. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

considered a near-natural hydrological condition since dam construction only starts at the beginning of the 20th century reaching the peak of disturbance in the mid 20th century (Azevêdo et al., 2004). The historical military thematic maps (1855), called the "Tágides" are a collection of eight maps with continuous coverage of 128 km along Tagus River on a scale of 1:20000. They were ordered by the Portuguese Queen Mary II to the Portuguese Military Institution to assess the navigability of Tagus River, which was considered in the 19th century as one of the most important routes of communication and transport in Iberia. Thus, all river morphological entities, including the fluvial corridor, the presence of geomorphic features like bars and islands, and the LULC along its margins, have their planforms (shape and size) represented in a scale-depended way (Fig. 2). The historical military thematic maps were georeferenced using ArcMap's Geo-referencing Toolbar. We selected the thin plate spline transformation since it is known as one of the most suitable transformation algorithms when georeferencing historical cartography (Brovelli et al., 2011). The thin plate spline transformation optimizes maps local accuracy, instead of global accuracy, by introducing some local alterations, since the algorithm considers the ground control points as precise. Since we were particularly interested in a high accuracy in river zone and surrounding areas, we used a set of homologous and unchanged control points, mostly located in river's vicinity, both in the historical and contemporary maps, namely water mills, the mouth of Tagus tributaries, old houses, bridges, churches and railways. The maximum average root means square error obtained, that describes the error of the georeferenced process, was 10, 7m. All the historical military thematic maps were projected to the Lisboa Hayford Gauss IGeoE coordinate system. For the other two dates (1940 and 2000) we also acquired military thematic maps, from the Portuguese Military Institution, now called Portuguese Military Geospatial Information Center – CIGeoE (https://www.igeoe.pt), since they have analogous graphical representations of river features, in a similar scale (1:25000), allowing the comparison of the river planforms, in all dates. The historical military thematic maps were then overlapped on the other two military thematic maps using ArcGIS 10.5. Tagus River was partitioned into 2500 m-long river sections (sampling units – SU), in a total of 13 SUs for the Upland zone, 11 SUs for the Middle zone and 27 SUs for the Lowland zone, for each date. The length of the sampling units was empirically selected in order to capture all the river's bend variability in the three studied zones. The length of the sampling units (2500 m) was empirically selected in order to capture the entire bend variability in the three studied zones.

2.3. Data collection on river morphology

A GIS was used to compute, store and organize all the river morphological data for the three dates. Four categories of metrics were used to describe the river morphology using the military thematic maps, namely Sinuosity, Geomorphic, Aquatic and Riparian (Table 2). Fig. 2 illustrates how these metrics were obtained by visual classification and manually digitalization of all the geomorphological entities and surrounding land-uses, using ArcGIS 10.5 software (ArcGIS, Copyright © Esri). Sinuosity and Riparian metrics were extracted and computed using linear measures (line vector format) while Aquatic and Geomorphic metrics were extracted using areas (polygons vector format). Since the historical military thematic maps of 1855 had a higher level of graphical detail compared with the military thematic maps of 1940 and 2000 (scale of 1:20000 *vs* scale of 1:25000, respectively) the Minimum Mapping Unit, that means the smallest polygon digitalized, were defined by the maps of 1940 and 2000 and was 150 m^2. The procedure for the extraction and computation of the geomorphological data was repeated for each SU, using the military thematic maps of 1855, 1940 and 2000, in a total of 1460 polygons and 3184 lines.

We applied the Shannon Wiener Index (H') (Spellerberg, 2008) as an indicator of morphological diversity, using the number and the percentage of all river elements observed in each SU, for all dates, as richness and abundance, respectively. For the aquatic and geomorphic metrics we used the percentage area of each element within each SU, while for the riparian metric we used the percentage of the river margin covered by riparian woody vegetation in each SU. Shannon Wiener Index was recently used to assess the geomorphic diversity changes (substrate diversity) in restored river systems (Addy and Wilkinson,

Table 1
Main geological and contemporaneous morphological characteristics of the three studied river zones in Tagus River. Classification of planform type according to Rinaldi et al., 2016. N describes the number of Sampling Units (SU) per river zone.

Zone	Geological background	Valley confinement	Drainage area	Predominant bed material size	Planform type	River type	Mean slope	Elevation range	Stream order
Upland N = 13SU	Eruptive and metamorphic formations	Confined to partly confined	59 144 km2	Boulder and cobble	Single-thread: Straight to sinuous	High energy and non-cohesive	15.69%	39–1100 m	5–7
Middle N = 11SU	Metamorphic and sedimentary formations	Partly confined	62 200 km2	Gravel and sand	Single-thread: Sinuous	Medium energy and non-cohesive	11.34%	20–620 m	7
Lowland N = 27SU	Sedimentary formations	Unconfined	71 045 km2	Sand, fine sand and silt	Transitional: Single-thread -meandering to transitional -wandering	Low energy, and cohesive	7.53%	0–675 m	8

2019). Although individual river elements may show high turnover, depending on natural successional phenomena, according to Ward et al., 2002, the relative abundance of channel forms in natural river corridors tends to remain constant over long time periods. Thus, a reduction in the Shannon-Wiener morphological diversity reflects a decrease of the instream habitat diversity and a reduction of the river's lateral hydrological connectivity with the floodplain, thus, degradation, from the ecological functioning point of view.

2.4. Human drivers of river morphological changes

Changes in the natural flow and sediment regimes are the most important human drivers of river morphological alterations (Ward and Stanford, 1995; Gregory, 2006; Burge, 2007; Corenblit et al., 2015). Two sets of explanatory variables, describing hydrological and LULC changes, were calculated for each sampling unit (SU), in each date, in order to relate the river morphological changes of Tagus River to the effect of human activities in (1) hydrological data, (2) LULC.

2.4.1. Hydrological data

Most of the historical hydrological records of Tagus River were lost during wars and in the fires that occurred as a consequence of the big Portuguese earthquake of 1755. The oldest existing records are from 1872 but they show many flaws. From this period onwards, the existing hydrological information from Tagus River lacks of long continuous data, as well as simultaneous operating periods of its gauging stations (Azevêdo et al., 2004). Furthermore, the existing gauging stations are too far apart for the necessary detail to determine accurately the daily flow regime in every of the 51 sampling units. Thus, in this study hydrological data were computed by simulating river flow regime using the Soil and Water Assessment Tool (SWAT) model through the ArcSWAT interface (Olivera et al., 2006). SWAT is a catchment-scale model, physically based and timely continuous, used to forecast hydrological, sediment transport, nutrient and pollution loads in watersheds (Gassman et al., 2007) allowing long-term studies in rivers (Dile et al., 2016). Furthermore, SWAT has been used, in more than four hundred Peer-Review Journal Articles, for hydrologic modelling purposes. In this study, the watershed modelling was performed accounting only for the Portuguese area of the Tagus River basin. The river discharges coming from the Spanish area of the Tagus River basin were inputted into the model using gauging data recorded near the border (gauging station of Vila Velha de Rodão, provided records from 01/10/1903 to 31/03/1974 and Nossa Senhora da Graça from 27/07/2001 to 28/10/2017). By these means, it is possible to take into account the effects of the Spanish side of the basin while increasing the accuracy of the model results with recorded data. A digital elevation model (DEM) with an accuracy of 25 m was used (available at: http://land.copernicus.eu, consulted on May 2018). The hydrographic network was built from the error corrected DEM, in which the sub-basin of each river stretch corresponds to approximately 0.1% of the overall river basin. Soil information was attained from the Direção Geral do Território (available at http://www.dgterritorio.pt, consulted on May 2018). Land-use was considered static during the period under analysis since the proportional LULC changes, when taking into account the entire watershed dimension, had no significant effects in the hydrology modelled for each sampling unit. Meteorological data were obtained from the Global Weather Data for SWAT (Fuka et al., 2014) and from high-resolution grids with monthly climatic observations (referred to as CRU TS dataset) (Harris et al., 2014). Global Weather Data provides daily records in SWAT file format over a 36-year period, from 1979 to 2014, whereas CRU TS dataset provides monthly data for a complete century (1901–2018). Accordingly, for the scenarios encompassing the period of 1979–2014, data was used directly from Global Weather Database. For the remaining scenarios, data was transformed to meet the corresponding monthly records observed on that period accordingly to CRU TS. Slope definition was done according to 4 percentage classes

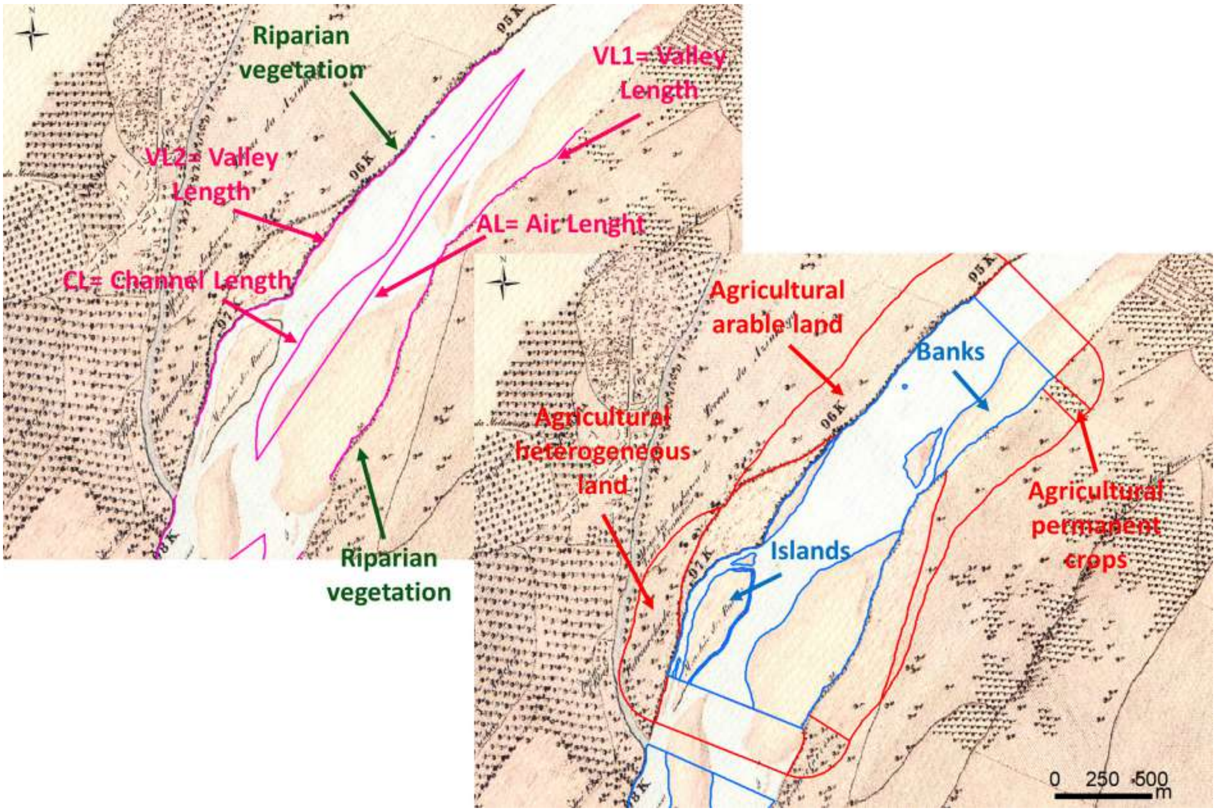

Fig. 2. Illustration of the historical military thematic maps of 1855 for the Sampling Unit 32. Illustration of the morphological features and LULC classes in the 250 m-buffer, manually mapped: Green arrows: Riparian vegetation; Pink arrows: Channel Length, Valley Length and Air Length; Blue arrows: Banks and Islands, Red arrows: Agricultural arable land, Agricultural heterogeneous land and Agricultural permanent crops. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

evenly distributed. The model hydrologic response units (HRU) – homogeneous areas in terms of hydrological, land use, topographical and soil characteristics – were defined as multiple

HRU's with a threshold of 10% for LULC, soil and slope classes (Winchell et al., 2010; Dile et al., 2016). In the end, we obtained 3098 HRU's from a total of 494 sub-basins.

The model was calibrated for the period between 01 and 10-1943 and 31-07-1949 with a warming period of one year. Calibration results were compared with observed data in the gauging station of Ponte de Santarém. The model was furthermore validated in the Almourol gauging station for the period of 10-October-2000 to 30-September-2004, with a previous 5 year warming period (Fig. 3). Model accuracy during calibration and validation was evaluated by analysis of the coefficient of determination (R^2) and the modified Nash-Sutcliffe efficiency (mNSE). Both R^2 and Nash-Sutcliffe efficiency (NSE) is the most widely used statistics reported for SWAT's calibration and validation (Arnold et al., 2007) and have been recommended for this analysis (Coffey et al., 2004). The R^2 stands for the amount of variance of the observed data that can be predicted by the model and is standard procedure to measure how well the model can replicate the reality. The NSE is a measure of the residual variance magnitude and is computed by the ratio between the residual variance and the measured data variance (Moriasi et al., 2007). However, NSE is highly influenced by extreme flows and therefore was not used. Instead, we calculated the mNSE, a modification of NSE that is largely used to overcome the NSE oversensitivity to extreme values (Krause et al., 2005). Calibration achieved in the gauging station of Ponte de Santarém R^2 and mNSE values of 0.69 and 0.57, respectively, for monthly flow data. Usually, R^2 and mNSE above 0.50 are considered as satisfactory for a monthly time step (Henriksen et al., 2003, Moriasi et al., 2007) and can be considered as acceptable calibration for hydrologic modeling (Engel et al. 2007). The validation attained in the Almourol gauging station an $R^2 = 0.97$ and a mNSE = 0.83 for monthly flow data. This stands for a very good result concerning R^2 and mNSE. Therefore, in both cases, the achieved results regarding R^2 and mNSE fulfill the requirements for acceptable results (Santhi et al., 2001; Moriasi et al., 2007, Kouchi et al., 2017).

After calibration and validation, flow regime (daily data) was computed for the 51 SU, using 10-year periods, namely 01–October–1904 to 31–July–1914 for the Old date, 01–October–1934 to 31–July–1944 for the Int date, and 01–October–2004 to 31–July–2014 for the New date. Then, four hydrological variables representing the magnitude, duration, and amplitude of discharges were determined for each period, in each SU: (1) Average flow (AveFlow) defined as the average of the monthly flows; (2) Average of yearly amplitude (AmpFlow) defined as the average of the differences between the maximum and minimum monthly flows in each hydrological year (from October to September); (3) Wet season (WetSeas) calculated as the average across the years of the sum of the flows between November and February; and (4) Dry season (DrySeas), calculated as the average of the sum of the flows between June and September.

2.4.2. LULC data

LULC data were obtained by on-screen digitizing of military thematic maps in all dates combined with bibliographic references for the Old-1855 and Int-1940 dates (Guerra, 1861; Silbert, 1978; Dias, 2010) and using Corine Land-cover 2000 and World Imagery Layer (ArcGIS data Center) for the New-2000 date. Homogeneous LULC patches were manually mapped in a 250 m-buffer surrounding each sampling unit. The 250 m wide criterion was selected by taking into account cartographic restrictions imposed by the historical military thematic maps (maximum mapped width in the Upland zone). Then, LULC patches were aggregated in six classes according to the maps' legend available

Table 2
Category, designation, acronym, and rationale of structural river morphological metrics used in this study.

Category	Structural planform metric	Acronym	Proxy for river morphology	References
Sinuosity	Channel Sinuosity Index CSI = CL/AL, where CL = Channel Length of each SU AL = Air Length the shortest air distance of each SU	CSI	Channel meandering intensity; flow capacity and sediment dynamics.	Mueller, 1968; Ghosh and Mistri, 2012.
	Valley Sinuosity Index VSI = VL/AL, where VL= (VL1 + VL2)/2 VL1 = Valley Length in the left margin VL2 = Valley Length in the right margin AL = Air Length the shortest airdistance of each SU	VSI	Valley meandering intensity Floodplain roughness	
Aquatic	Aquatic Main and Secondary Channel Total area occupied by water surfaces with upstream and downstream connections with the main channel, in each SU	AMS_TA	Active cannel Lotic segments	Brooker, 1985; Ward and Stanford, 1995; Ward et al., 2002
	Aquatic Lateral Channel Number of water surface patches with a unique connection with the main channel (upstream or downstream), in each SU	ALC_Nump	Lateral hydrological connectivity with the floodplain. Lentic habitats- Key habitat for fish and other species	
Geomorphic	Bank (Number of Patches) Sediment accumulation patches locate inside the channel intermingled with water, in each SU	Bank_Nump	River adjustment, Sediment dynamics, River energy Instream habitat diversity	Gurnell and Petts, 2002; Dufour et al., 2015; Gonzáléz del Tanago et al., 2016
	Island (Number of Patches) Number of exposed land patches (rock and sediment materials) locate inside the channel totally surrounded by water, in each SU	Island_Nump	Sediment dynamics, Flow dynamics Instream habitat diversity	
Riparian	Riparian Longitudinal Connectivity (%) Percentage of the river margin covered by riparian woody vegetation, in each SU	RipLongC	Reciprocal morphological adjustments Lateral connectivity with the Floodplain	Corenblit et al., 2015; Gonzáléz del Tanago et al., 2016

in the military thematic maps: (1) Artificial surfaces including urban and industrial areas, roads, mines; (2) Agricultural arable land, including intensive irrigated and non-irrigated areas; (3) Agricultural permanent crops, including vineyards, fruit trees, and olives groves; (4) Agricultural heterogeneous land, including agroforestry areas and complex cultivation patterns; (5) Forests, including broad-leaved forests, coniferous forests and mixed forests; (6) Scrublands, including sparsely vegetated areas, sclerophyllous vegetation, herbaceous association, and transition woodlands-scrublands. LULC variables were evaluated in the percentage of area occupied in each SU.

We additionally combined LULC information extracted from the military thematic maps with the history of LULC changes in Tagus River described in historical bibliographic references (Guerra, 1861; Silbert, 1978; Dias, 2010). This ancillary information was used, not only to qualitatively validate the LULC changes at the valley level, but also to detail the vegetation communities or floristic composition described in the broad classes identified graphically in the legend of the military thematic maps.

2.5. Statistical analysis

For testing hypothesis H1 (*Morphological zone divergence*) we ran one-way ANOVA models using the factor time with three levels (Old, Int, and New) and as response variable each river morphological metric in each river zone. Then, for each zone, we used Tukey tests to identify the pairs of time (Old-Int, Int-New) where changes in metrics are significant. The computations and graphics were performed with the R software (R Core Team, 2018). ANOVA models were fitted with function *aov* while function *TukeyHSD* was used to obtain confidence intervals on the differences between the means at the three levels of factor time.

For testing hypothesis H2 (*Human-induced explanation)* we accessed the relative contribution of hydrological and LULC variables as predictors of the river morphological changes detected across time as follows: generalized linear models for each river morphological metric were fitted using as predictors the set of 4 hydrological and of 6 LULC variables; the R function *glm* with "gaussian" family for continuous metrics (VSI, CSI, AMS_TA, RipLongC, Diversity) and "poisson" family for discrete metrics (ALC_Nump, Bank_Nump, Island_Nump) was used; then the best submodel, in the sense of minimum Akaike Information Criterion (AIC) was found, using function *bestglm* from R package 'bestglm' (McLeod and Xu, 2018); the contribution of each set of variables (hydrological and LULC) was evaluated as the proportion of the number of selected variables in each set in the best submodel.

3. 3.Results

3.1. Morphological evolution in Tagus River

We observed a trajectory of overall morphological alteration in the three river zones, between the historical (1855) and the contemporaneous date (2000). Our results confirmed that morphological changes showed different magnitudes and trajectories of variation in the diverse river zones (*Hypothesis 1*). Both hydrological and LULC changes contribute to the significant morphological changes in Tagus River (*Hypothesis 2*) although with distinct relative importance in the three river zones.

The most severe morphological alterations were observed in the geomorphic metrics, which are considered to be markers of river dynamics (Gurnell and Petts, 2002; Grabowski et al., 2014). We detected an accentuated reduction of the number of banks (Bank_Nump) and islands (Island_Nump), in all river zones, when comparing the Old date with the other dates (Fig. 4c and Appendix A: New = Int < Old). The exception was observed in the Middle zone where we found a higher number of banks in the most contemporary date (Fig. 4c and Appendix A: Int < New).

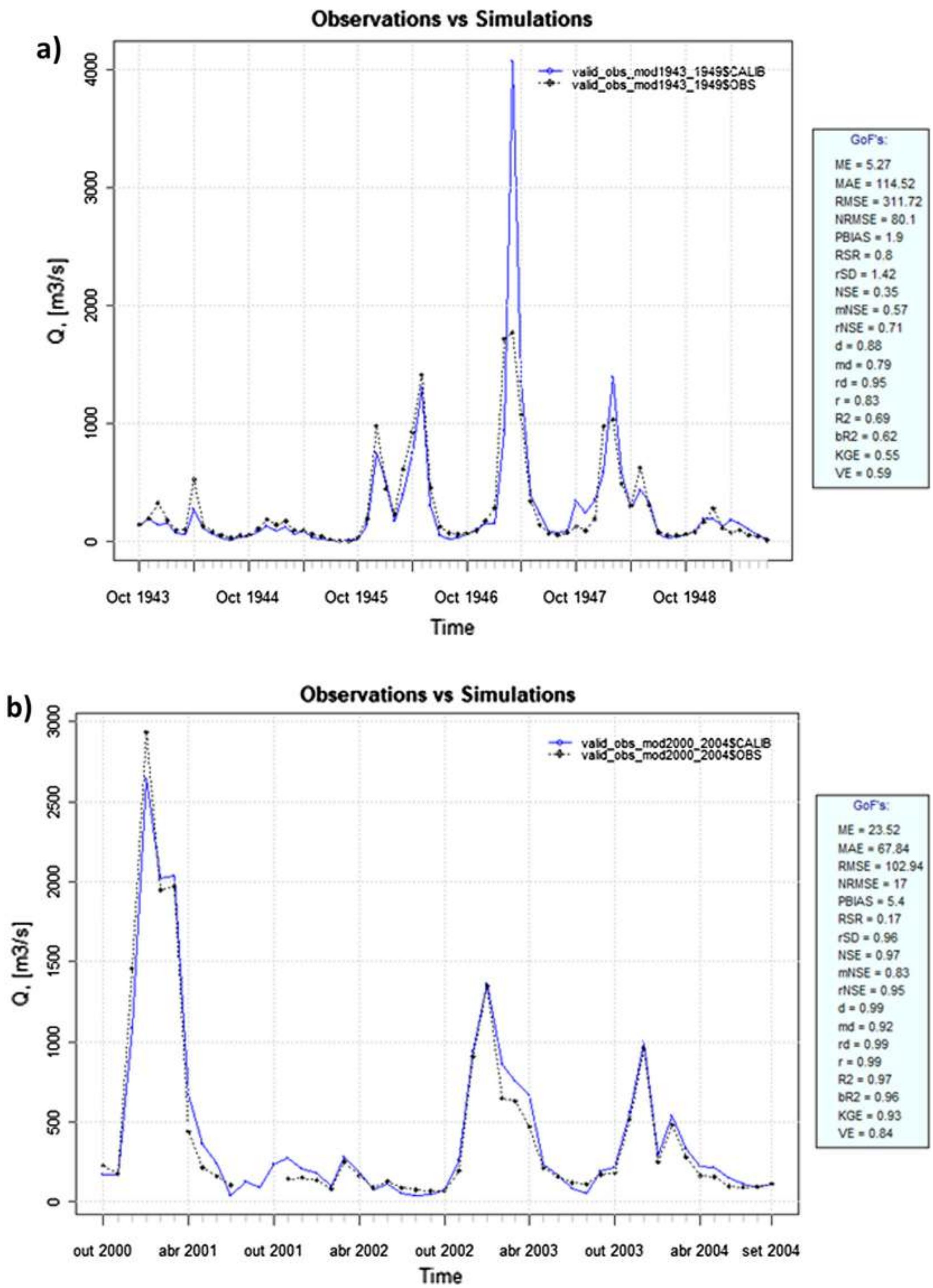

Fig. 3. Results for the hydrological modeling concerning (a) calibration plots for the period between 01 and 10-1943 and 31-07-1949 and (b) validation plots for the period of 10-October-2000 to 30-September-2004.

We also observed a decline in sinuosity metrics but especially significant for the Upland zone, and for the valley sinuosity metric (VSI) (Fig. 4a, Appendix B: New = Int < Old). On the other hand, the Middle zone showed a slight increase in valley sinuosity between 1855 and 2000, though these changes were not statistically significant (Fig. 4a, Appendix B).

For the Aquatic metrics, we observed a continuous decline in the number of lateral channels (ALC_Nump) in Upland and Lowland zones (Fig. 4b, Appendix C: New < Old). Middle zone showed an opposite pattern of a gradual increase in the number of lateral channels (Fig. 4b).

The AMS_TA metric, that describes the active channel width, showed significant alterations in Upland zone, mainly associated with the highest increase in the channel capacity in 2000, due to the backwater effect of Belver dam (Fig. 4b, Appendix C: Old = Int < New). Middle zone showed the highest channel width in the Intermediate date (1940) mainly related with the effect of high flows occurred during the winter of 1940 (Fig. 4b, Appendix C; Old = New < Int), while Lowland exhibited patterns of channel narrowing especially in the most recent date (2000), but the changes were not substantially evident in the latter zone.

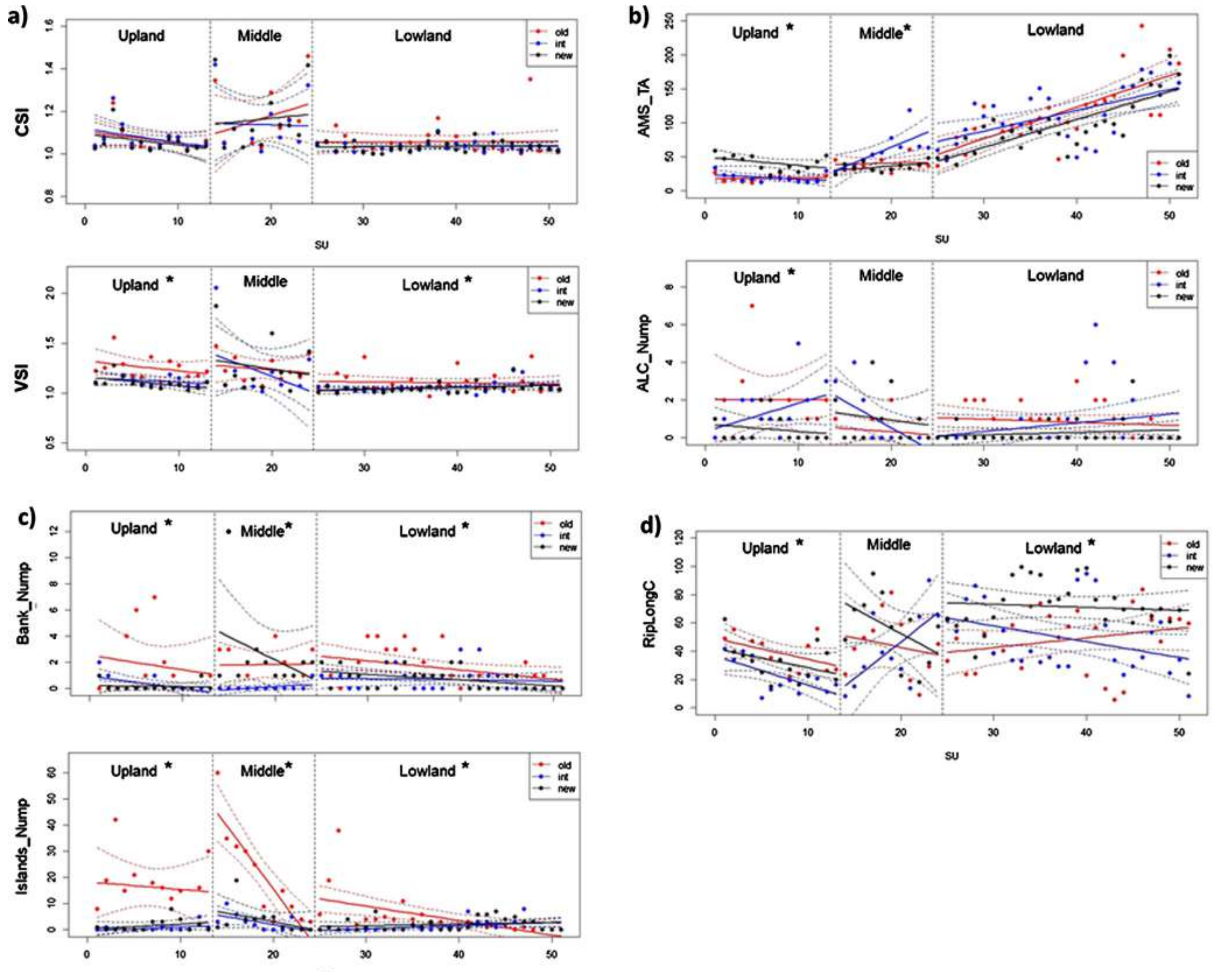

Fig. 4. River morphological evolution of Tagus River in the Upland, Middle and Lowland zones in the three dates: Old (1855), Int (1940) and New (2000). Full lines depict the linear trendlines while dotted lines depict the confidence bands (95% confidence) of the fitted linear model. (a) Sinuosity metrics, (b) Aquatic metrics, (c) Geomorphic metrics, (d) Riparian metrics. Significant changes are marked with * ($p < 0.05$ in one-way ANOVA models using the factor time with 3 levels).

We also observed a high variability on the pattern of Riparian vegetation metric among the three river zones. While in Upland zone the riparian woody vegetation shows the highest connectivity in 1855, followed by a decline in 1940 and a recovery towards 2000 (Fig. 4d, Appendix D: Int < Old), in Middle and Lowland zones the connectivity of the riparian galleries achieved the highest values in the most recent date (Fig. 4d, Appendix D: Old = Int < New).

The highest values for the Shannon-Wiener morphological diversity (H') were achieved in the Old date for the three river zones (Fig. 5). Upland zone showed the highest morphological diversity decay across time (Fig. 5, Appendix E). In this zone, all SUs showed a consistent morphological diversity decline and the highest losses were found in SU05 (H'New- H'Old = −0.9) and SU13 (H' New-H'Old = −0.8). Middle zone showed also a significant decline across time while changes in the Lowland zone were not considered statistically significant (Fig. 5, Appendix E).

3.2. Hydrological and LULC changes

Stream flow regime and LULC in Tagus River have changed along the 145 years of analysis. Tagus River showed an accentuated reduction of flow discharges when the Old date (1855- pre-regulation) is compared with the New date (2000- high regulation) (Fig. 6). The reduction of the high flows, especially peak flows, between the Old and the New date were also observed in all river zones (reduction of the maximum values obtained for the WetSeason variable) in Table 3. The highest values for the average flows were achieved in the Int period (1940- low-regulation) (Table 3). This period was characterized by high floods ($Q\ m^3\ s^{-1} > 10{,}000$) occurred mostly during the winter period (Benito, 2006; Loureiro, 2009). As a result of regulation by dams, Tagus River showed in New date an altered hydrograph, characterized by more water in summer (dry season) and less water in winter (wet season), when compared with the Old date that reflects the natural flow regime (Table 3).

As for LULC changes, we observed a global pattern of reduction of the natural areas due to agricultural intensification, urban expansion, and new forest plantations. However, the three river zones showed specific LULC changes (Appendix F). In 1855, the Upland zone of Tagus River was dominated by natural areas, mostly scrublands, chestnuts, oaks and cork-oak forests (88%). In 1940, these vegetation communities were replaced by Agricultural permanent crops (58%), mostly olive grove plantations that were established in the terraces of the steep-sided-valleys. Currently, due to rural abandonment caused by rural–urban migration, higher labor costs and an aging population, the Upland zone is composed by a mixture of these remaining olive grove areas (42%), along with sclerophyllous vegetation (30%), maritime

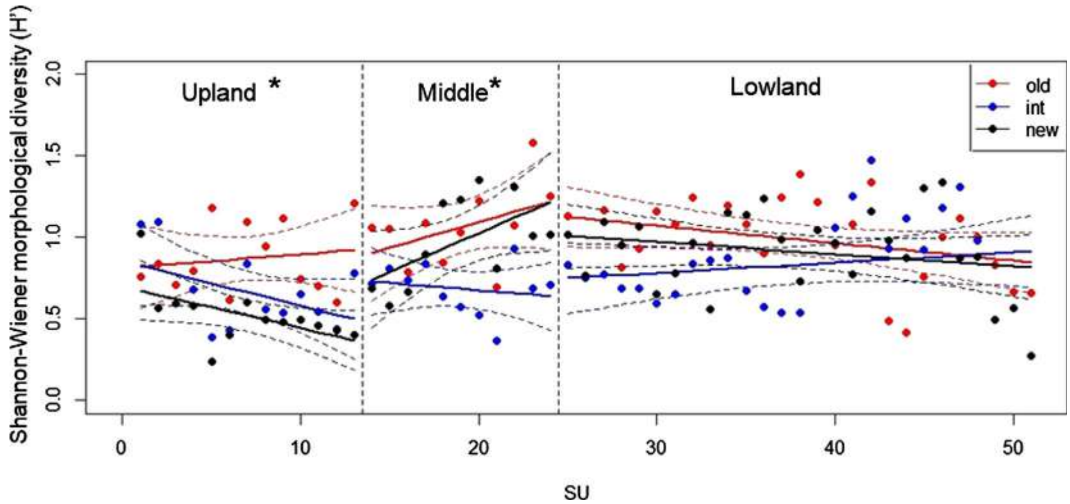

Fig. 5. Shannon-Wiener morphological diversity (H') of Tagus River in the Upland, Middle and Lowland zones in the three dates: Old (1855), Int (1940) and New (2000). Significant changes are marked with* ($p < 0.05$ in one-way ANOVA models using the factor time with 3 levels).

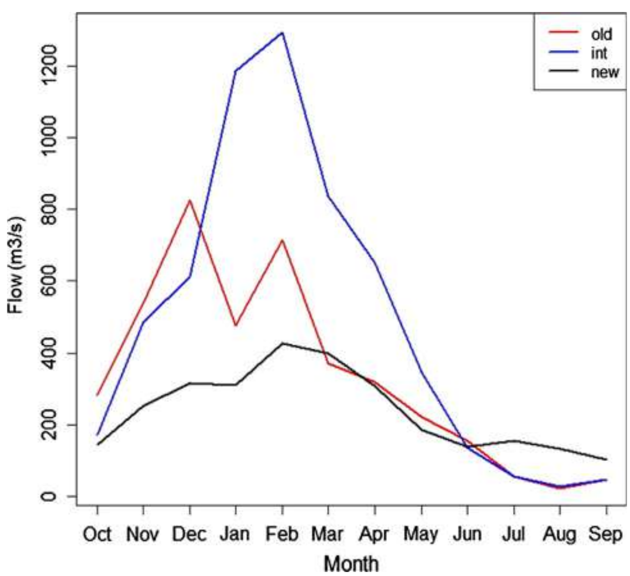

Fig. 6. Flow evolution (mean monthly flows) of Tagus River in the three time periods: Old (1855), Int (1940) and New (2000).

pine, and more recently, *Eucalyptus globulus* plantations (21%).

Middle zone was subjected to large LULC alterations. In 1855, river landscapes of the Middle zone were composed of a mixture of agricultural LULC (66%) followed by natural areas (32%). In 1940, these natural areas were replaced by heterogeneous agricultural LULC (89%), mostly subsistence farming systems, with potatoes, maize, and vegetables, cultivated in small parcels established in river margins. In 2000, this zone continued to have been dominated by agriculture LULC (73%), but part of these family farming systems was replaced by eucalyptus plantations (13%) along with urban and industrial areas (4%).

Lowland zone of Tagus River has been historically dominated by agricultural LULC. In 1855, the Lowland zone was mainly composed by extensive agricultural LULC (65%), mostly cereals cultivated in arable areas (42%) and complex agricultural systems (23%), including permanent crops and other agricultural heterogeneous areas. Nevertheless, scrublands and broadleaves forests represented 33% of the total area. In 1940, we detected a replacement of the natural scrubland communities, by intensive irrigation crops including cereals, orchards, vineyards, and olive grove plantations. In 2000, the Lowland zone remains dominated by irrigated crops (89%), but some permanent plantations were replaced by urban settlements (2%) and eucalyptus plantations (4%).

3.3. Contribution of hydrology and LULC to morphological changes in Tagus River

Hydrological variables were identified as the main predictors of the morphological alterations when compared to LULC variables (the percentages of the number of variables of each type, used in the best fitted submodels for each river morphological variable, are 63% and 37%, respectively) (Fig. 7, Appendix G). From the seven best submodels fitted for each river zone, we obtained six significant models for the Upland zone, three significant models for the Middle zone and six significant models for the Lowland zone (Appendix G). Variable AveFlow was the hydrological predictor selected more often by the best fitted linear submodels of river planform variations. The proportion of the number of hydrological and LULC variables selected as predictors of morphological changes varies on the diverse river zones. In Upland zone, morphological alterations were mainly ruled by hydrological variables, especially by AveFlow, AmpFlow and DrySeas. On the contrary, changes in Lowland zone are associated with a combination of hydrologic and LULC variables. Particularly, AveFlow, WetSeas and DrySeas, and the intensive LULC, like Arable Land, were mainly linked to the observed planform changes. In the Middle zone, AveFlow and AmpFlow largely contributed to the observed planform changes, although the occurrence of Arable Land and Eucalyptus plantations, were also associated with changes in river morphology.

4. Discussion

4.1. Tagus morphological changes across space and time

In this study, we used a planform approach to reconstruct the evolutionary trajectory of the Tagus River, from 1855 to 2000, in three river zones. Segment level hydrological and LULC changes were used as a proxy to human-induced river channel morphological alterations.

We detected an overall river morphological alteration between the historical and the contemporaneous dates characterized by channel narrowing, sinuosity reduction, a decrease in the number of banks and islands, and abandonment of secondary channels. Until the mid-19th century, Tagus was a highly dynamic river, having a braided character with branched channels separated by large sand bars (Azevêdo et al., 2004, 2009). However, after this period, the increase of human activities changed the morphological pattern of the Tagus River until the current situation characterized by a single-thread and low sinuosity

Table 3
Mean, maximum, minimum and standard deviation for the hydrological variables, in each zone and in each period.

River zone	Hydrological variable	Indicator	Old 1855	Int 1940	New 2000
Upland	Average flow	min	306.89	426.77	169.97
		max	319.59	451.29	202.78
		mean	314.16	441.39	191.88
		std. dev.	5.80	10.44	12.07
	Average of yearly amplitude	min	1118.05	1563.55	345.20
		max	1145.41	1634.89	439.09
		mean	1132.98	1606.68	417.24
		std. dev.	12.77	29.38	27.90
	Wet season	min	2105.18	2828.04	810.26
		max	2188.93	2966.89	1007.07
		mean	2154.15	2906.99	945.30
		std. dev.	36.76	62.29	69.69
	Dry season	min	250.98	217.90	395.94
		max	254.42	240.24	401.05
		mean	252.91	235.98	398.98
		std. dev.	1.59	6.24	1.83
Middle	Average flow	min	320.16	452.80	203.88
		max	323.26	460.80	208.58
		mean	321.75	456.83	206.34
		std. dev.	1.01	2.65	1.52
	Average of yearly amplitude	min	1146.99	1639.15	440.65
		max	1155.78	1662.96	446.87
		mean	1151.43	1651.10	443.94
		std. dev.	2.87	7.87	2.01
	Wet season	min	2192.84	2976.81	1012.70
		max	2213.11	3030.62	1034.54
		mean	2203.25	3003.81	1024.32
		std. dev.	6.65	17.81	7.08
	Dry season	min	254.32	240.60	401.77
		max	254.61	242.97	405.41
		mean	254.47	241.81	403.67
		std. dev.	0.08	0.78	1.16
Lowland	Average flow	min	356.36	523.11	276.20
		max	372.73	562.27	286.05
		mean	361.80	537.01	280.30
		std. dev.	4.80	11.53	2.94
	Average of yearly amplitude	min	1227.31	1842.08	554.56
		max	1271.36	1968.15	581.35
		mean	1243.36	1887.49	565.62
		std. dev.	13.09	37.14	7.88
	Wet season	min	2418.40	3431.49	1355.28
		max	2524.52	3695.11	1406.69
		mean	2454.99	3526.35	1376.37
		std. dev.	31.11	77.73	15.09
	Dry season	min	257.14	266.57	536.64
		max	262.73	271.47	538.60
		mean	260.13	267.99	537.68
		std. dev.	1.78	1.45	0.62

river with alternate bars. Similar morphological alterations have been also identified and related with human activities in many European rivers (Liébault and Piégay, 2001; 2002; Rinaldi, 2003; Surian and Rinaldi, 2003; Uribelarrea et al., 2003; Surian and Cisotto, 2007; Magliulo et al., 2016 Roccati et al., 2019). These changes can be largely attributed to river flow regulation and the consequent changes in sediment dynamics, with noticeable effects both downstream and upstream of dams.

According to our results, hydrological alterations, namely the substantial diminish of the average discharges (AverFlow) and the decrease in the discharges that occurred during winter (Wet Season), were identified as the main drivers of Tagus morphological changes. In fact, the high frequency and magnitude of large floods were frequently mentioned in the bibliography as the source of the historical high channel mobility of Tagus River (Uribelarrea, et al., 2003; Azevêdo et al., 2004, 2009). The current reduction of sediment inputs associated with the decrease of productive floods are now the major constrains for the morphological dynamics, not only for Tagus but also for many rivers at European scale (Rinaldi, 2003; Surian and Rinaldi, 2003; Uribelarrea et al., 2003, Picco et al., 2017). These constrain may be intensified in the current context of climate change where river discharge is predicted to decrease for Southern Europe (IPCC, 2018). Nevertheless, the major contribution of hydrology compared to LULC in the morphological alterations, identified in this study (63% *vs* 37%, respectively), cannot be indubitably supported since it is difficult to unravel the diverse sources of variation.

Morphological changes were also correlated with combined sources of anthropogenic modifications in the fluvial system in other regions of the world (Mendoza et al., 2019; Ferreira et al., 2019). LULC alterations also promote a significant effect on soil erosion rates and sediment supply to rivers (Bakker et al., 2008; Foucher et al., 2014). LULC occupation in Tagus catchment is associated with the history of civilization in Tagus valleys. The peak of deforestation was achieved in the mid-19th century where timber was used for the construction of the Portuguese railway line (Azevêdo et al., 2004, 2009; Guerra, 1861). This process leads to the continuous silting up of the riverbed and for the development of the large sand bars throughout Tagus River. However, the impact of the dams after mid-20th century forward leads to a reduction of the sediment supply. In this study, LULC changes were analysed at a 250 m-buffer surrounding river and at three dates between 1855 and 2000. The ancillary bibliographic records support the observed patterns of agriculture intensification, the increase of forest plantations and the reduction of the Mediterranean scrublands for wider areas of Tagus valleys (Guerra, 1861; Silbert, 1978; Dias 2010). Additionally, similar patterns of agricultural intensification, urban expansion and increase of forest management plantations were also reported in historical LULC studies for the Mediterranean region, where Tagus river basin is included (Ferreira et al., 2019).

One of the most evident results of the fluvial landscape alteration observed in this study relates to the instream geomorphic units. We found a generalized decrease of 41% on the number of banks and 79.9% on the number of islands when comparing the historical and the contemporaneous dates. We also observed a reduction in ca. 50% of the area occupied by islands and banks on the Tagus Lowland zone in relation to the 18th century (Dias, 2010).

The work of Azevêdo et al. (2004) refer that during the natural river regime, occurred before dam construction, it was possible to verify that the migration of the sand bars was in the order of 0.5 m/decade. Variation in channel sinuosity and in the numbers of lateral channels was detected, however not significant for all river zones. For instance, the average of Tagus's channel sinuosity only decreases from 1.08 in 1855 to 1.06 in 2000, an almost invariable alteration, while a decrease of 54% in the total number of lateral channels were found between 1855 and 2000. Patterns of sinuosity loss and floodplain disconnection were also observed in other rivers systems as a result of river adjustments to flow alterations (Kondolf, 1997, Gregory, 2006). But in-channel conditions may be driven not only by the longitudinal dynamics of the in-channel flows. LULC alterations, especially in the river's vicinity may affect in-stream conditions, like channel sinuosity, since affect roughness characteristics of the floodplain (Lazarus and Constantine, 2013; Lallias-Tacon et al., 2017) as well as bank erosion and stabilization of river margins. Dufour et al., 2015 also suggested the relevance of local factors over basin-scale factors on river morphological changes in a study conducted on the Magra River (Central–Northern Italy).

Riparian vegetation changes also cause morphological adjustments in fluvial channels (Lazarus and Constantine, 2013; Corenblit et al., 2015; Gonzáléz del Tanago et al., 2016; Lallias-Tacon et al., 2017). In this study, riparian connectivity was highly altered over time throughout theTagus River zones. Riparian vegetation reciprocally interacts with fluvial processes by causing changes in sediment transport and in the physical morphology of the river channel (Corenblit et al., 2015; Gonzáléz del Tanago et al., 2016; Picco et al., 2017). The increase of the riparian connectivity promotes a redistribution of flow resistance by changing the flow velocities, the bank strength, the bar sedimentation, and the concave-bank bench deposition, which in turn promote

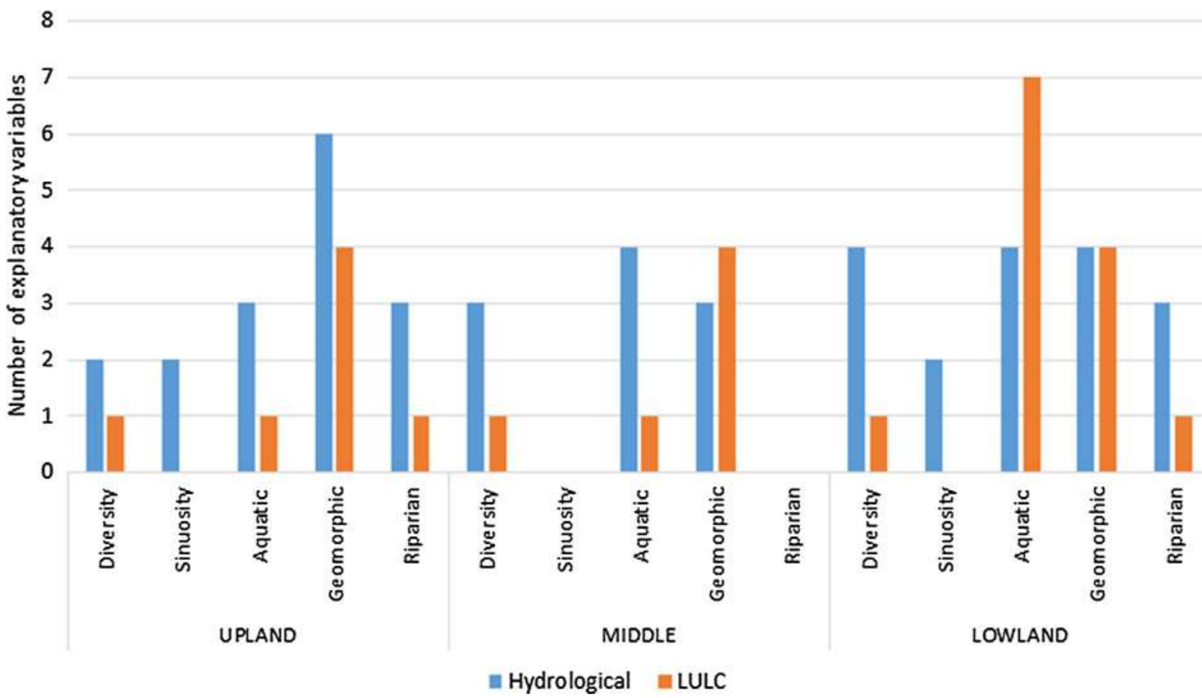

Fig. 7. Relative importance of hydrological *vs* LULC variables for the morphological metrics Diversity, Sinuosity, Aquatic, Geomorphic and Riparian, in each river zone. The height of each bar in the graphic is the number of explanatory variables of each type that are selected in the best linear submodel for each set of morphological metrics (only in significant models).

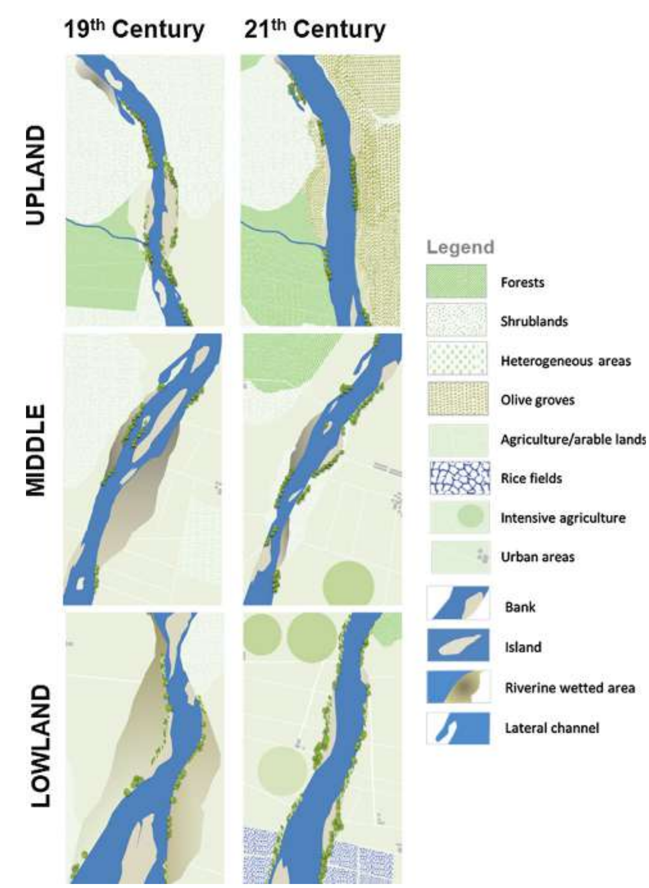

Fig. 8. Schematic representation of the Tagus River morphological evolution and proximal LULC changes, in each river zone from the 19th century to the 21th century.

alterations of the in-stream features. Moreover, riparian vegetation displays diverse responses to human disturbance at different timescales (Corenblit et al., 2015). In Piave River, Italy, the effects of human pressure also produced more stable riparian vegetation (Picco et al., 2017). In Mediterranean rivers subjected to dam-induced regulation, large patches of riparian vegetation occupy the formerly waterlogged riverbeds – the well-known phenomenon of *riparian encroachment* downstream of storage reservoirs (Kondolf, 1997; Aguiar et al., 2016). Riparian vegetation tends to colonize the stabilized banks and islands and encroach into the river channel due to the diminishing of flushing flows. The abandonment of subsistence farming systems, prevailing in 1855 and in 1940, usually developed nearby the river, also allowed the riparian expansion towards the valley in the current date. Although we observed the intensification of the agricultural land-uses, especially in Middle and Lowland zones, current agricultural activities are mostly mechanized and developed in a more distal buffer, decreasing farming activities in the areas closer to the riparian corridor. However, the increase of the riparian longitudinal connectivity does not lead necessarily to an improvement of river health since floristic diversity losses and alien plant invasions have been found in these riparian stands (Aguiar et al., 2016).

A novelty of this work was the application of the Shannon Wiener Index (H') as a descriptor of the morphological diversity and its relation with the river ecological functioning capacity. A consistent pattern of morphological diversity decline was observed along the 145-year period under analysis for the three river zones. The interactions between hydrological alterations and LULC changes jointly mediate the physical structure and the dynamics of river morphology. Besides the observed simplification of Tagus's channel morphology (narrowing and development of single-thread channel), those man-induced effects also promotes a decrease of the instream habitat diversity and a reduction of the river's lateral hydrological connectivity with the floodplain (reduction of ALC_Nump, Island_Nump and Bank_Nump), reflecting an overall degradation of the ecological functional capacity of Tagus River. Patterns of morphological degradation are frequently associated with negative impacts on rivers' ecosystem functioning (Elosegi, and

Sabater, 2013).

Despite the overall morphological changes, Tagus underwent different evolutionary trajectories in the three studied river zones (Fig. 8). High morphological alterations were more noticeable in Upland zone than in Middle and Lowland zones. The morphological modifications in the Upland zone, such as the reduction in the number of banks and islands, sinuosity decrease, the decline in the number of lateral channels and the enlargement of the active channel width, can be attributed to the artificial inundation of this zone by the backwaters of Belver and Fratel reservoirs (Fig. 1). Upland zone suffered a continuous and severe process of river stagnation, after the commissioning of Belver and Fratel dams (1951 and 1974, respectively), switching from a historical high energy zone, to a low-dynamic zone. Deforestation in this region was particularly severe, and although we detected an augment of the total area occupied by forests in the contemporaneous period, these areas are mostly composed by eucalyptus plantations, thus high intensive human-managed land-uses with increase soil erosion and sediment supply to the river.

Middle zone showed high morphological variability across time. Belver and Fratel dams regulate stream flow, particularly beheading the major floods, which were largely responsible for the historical channel dynamics (Azevêdo et al., 2004, 2009). All the sediment transported by source tributaries, mostly located in the left margin, like Ribeira do Alcolobre, Rio Torto and Ribeira de Coalhos that end immediately downstream of these dams is conveyed through the hydrographic network and deposited in the Tagus main channel, whose decreased flows are not able to wash this sediment downstream. Therefore, Middle zone showed a significant increase in the number of banks when compared to the Old and the New date, and this increase is particularly evident in the sampling units downstream of the Belver dam (SU 15 to SU19, Fig. 3c). In this zone we also observed an accentuated reduction in the number of islands when compared the Old with the other two dates. The islands observed in this zone, in the historical military maps of 1855, correspond mostly to small patches of bedrock and alluvial sediments inside the channel which diminution may be related with the great engineering works performed at the end of the 19th century by Brigadeiro Guerra in order to make the river navigable and to weaken the flood flow energy (Azevêdo et al., 2004). Nevertheless, local geological constraints, like the valley confinement and site-specific physical resistance and resilience conditions affecting sediments and flow discharges and their interrelations may also explain the morphological variability in the Middle zone beyond the influence of anthropogenic activity (Bridge, 1993; Gonzáléz del Tanago et al., 2016; Magliulo et al., 2016).

In the Lowland zone, morphological alterations were mainly characterized by channel narrowing, sinuosity decrease and reduction in the number of banks. Similar patterns of channel width decrease, sinuosity reduction and diminution of sediment deposition are usually referred as the main consequences of the combined effect of dam construction and land-use changes, in other alluvial areas (Uribelarrea et al., 2003; Rinaldi et al., 2005; Fortugno et al., 2017). Moreover, local physical modifications to prevent flood damages or to increase the agricultural area in river margins, likely to explain the observed morphological changes of Tagus between 1855 and 2000. These modifications included hard engineering works, such as the construction of dikes, ditches and small-sized dams, and were mostly performed in the second half of 19th century in order to reduce the flood flow energy (Guerra, 1861).

4.2. Drawbacks and limitations of the historical cartography

Historical maps can be a valuable resource in the characterization of river landform changes and for understanding past hydromorphological processes (Taillefumier & Piégay, 2003; Forget, 2013; Uribelarrea et al., 2003; Zlinszky & Timár, 2013; Ziliani & Surian, 2016. However, to find comparable maps is challenging, since most of the river historical cartography describe fluvial corridors from an artistic perspective missing the required planform geometric accuracy. Additionally, a large number of historical maps only represent small sections of the river, selected for a particular historical or cultural reason (e.g. the mount of the river, the location of fluvial ports, the position of obstacles for navigation), inhibiting large-scale analysis. In Portugal, rivers have been historically related to territory defense and mobility issues and thus the available cartography has been produced by the Portuguese Military Institution (CIGeoE) since the XVII century. This public institution is a certified cartographic authority and it is responsible for the production of the military maps, the only full thematic coverage of the Portuguese continental territory at a scale of 1: 25000. Although mapping techniques in Portugal have been evolving, from the exclusively field classical procedures, used to produce the military maps in 1855, until the use of aerial photography, after the 40 s, and the analysis of satellite images after the 90 s, the military maps maintaining equivalent legends and similar graphical representations of landscape entities and river features, allowing the comparison of landform changes between dates. However, differences in the map's scale may be a potential source of errors. In this study, the military maps of 1855 were produced with a higher level of spatial detail when compared with the military maps of 1940 and 2000 (1:20000 *vs* 1:25000, respectively). Thus, to achieve a common level of analysis the thresholds for the establishment of the Minimum Mapping Unit were defined by the maps with less graphical information. In addition, the georeferencing process may also bias the data. Georeferencing historical images is challenging and time-consuming since in most cases historical maps do not contain the spatial coordinates. Control points should be uniformly distributed along the maps, but in this study a particular attention was devoted to the identification of unchanged points, between historical and contemporaneous maps, in rivers' vicinity, to reduce the distortion errors in the target area (Aguiar et al., 2016). For instance, sinuosity metrics could be particularly sensitive to the curvature or bent distortion introduced during the georeferencing process. Nevertheless, the level of spatial detail in the historical datasets always determines the overall level of analysis in the study.

In long-term historical studies the ancillary information contained in books, photos or journals can be relevant to complement or validate the patterns of changes detected by the interpretation of historical maps. In this study, this information was particularly important to qualitatively corroborate the patterns of LULC change observed in the 250 m-buffer for wider areas of Tagus valleys. For instance, while the graphical legend of the military maps only identified coarse LULC classes, like the "Forest" class, the consulted bibliographic references allowed the characterization of the dominant vegetation communities of these forest areas, for each river zone, in each time period.

Despite the relevance of historical cartography for the characterization of the river landscape's history, it can only be considered as snapshots in time. Since morphological characteristics are flow-stage dependent, a degree of uncertainty is introduced when historical maps are used, since the precise relation between formative discharge and river mapping remains unknown (Bridge, 1993). In this study, it was not possible to incorporate differences in the seasonal river morphology that result from the intra-annual hydrological variability. All military maps represent river dimensions, forms, and features at the beginning of the Spring period (regular active channel width). In addition, only three snapshots of times were analyzed and thus it is not possible to characterize in detail the evolution of Tagus River in 145 years. Local detailed studies using more dates and covering larger temporal windows would likely reveal greater alterations of river morphology and would improve the accuracy of the trajectory of change of Tagus River landforms.

5. Conclusions

This study highlights several commonalities of morphological changes and their prime causes between the studied zones of Tagus River. Specifically, altered sediment dynamics and dam-induced reduction of constructive flood events caused an overall reduction of the number and extension of instream geomorphologic units and create a simpler and less dynamic river system when compared to the situation in the 19th century. LULC change was conspicuous in the 145 years study period and also contributed to the overall alteration in the morphology of Tagus River. In particular, the observed decrease of rain-fed agricultural lands and the diminution of subsistence farming systems and Mediterranean woods in Tagus River valleys affected sediment production and induced less fragmented riparian corridors. Notwithstanding the overall alteration of the historical river morphology, river zones display diverse magnitudes and types of adjustments and differ in the timing that major changes occurred. The Middle zone was particularly dynamic across time and over space, displaying varying (and complex) gradients of change, whereas the Lowland was featured by constancy and the Upland zone by the major and most consistent spatial and temporal alterations. Nevertheless, the morphological changes detected in this study reflect not only the Portuguese human influence but all the pressures and impacts received along the Spanish side.

Historical planform studies can be supportive of a morphological referential to the restoration of degraded sections of large rivers. Trajectories of the evolution of the morphologically-dependent aquatic and riparian ecosystems should be built upon these findings, taking into account the river zones' specificities and their interplay, as well as the effects of climate change and global change for better planning of river management. By calculating the current deviation in relation to a reference historical situation, we can obtain the degree of ecological loss associated with morphological alterations. For instance, the metric "morphological diversity" can be used as a combined measure of the overall structural morphology and as an indirect measure of the ecological functioning capacity of the river. This could be particular useful to complement the ecological quality assessment of large rivers.

Future prospective research concerning the evolution of large rivers should also integrated other aspects of human activities' effect together with hydrology and LULC changes. In many European rivers, sand and gravel mining, channelization, hydraulic works and construction

of bridges, have been responsible for a significant reduction in fluvial sediment supply which was likely to explain particular aspects of river morphodynamics and ecological functionality changes, especially after mid 20th (Surian et al., 2009; Roccati et al., 2019). The integration of historical analysis with remote sensing data and the creation of more detailed evolutionary trends using other historical sources (such as historical photos, parish memories, topographic measurements, and geomorphological surveys) could also unravel the insights of how past and present human alterations affect morphological processes in river-floodplain systems.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2020.104466.

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